FLOOD FREQUENCY AND MAGNITUDE ESTIMATES BASED ON VALLEY FLOOR MORPHOLOGY AND FLOODPLAIN SEDIMENTARY SEQUENCES: THE TYNE BASIN, N.E. ENGLAND

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ABSTRACT

This study examines the sedimentary and morphological flood record of the River Tyne, northern England, over the last 400 years. Temporal trends in flooding and spatial variations in the timing and nature of river response to floods (flood "effectiveness") are investigated at 3 reaches representative of upland, piedmont and lowland locations in the Tyne catchment.

Deposition of *coarse* flood sediments in *headwater* tributaries of the River Tyne appears to be strongly related to flood water:sediment ratios that is primarily controlled by sediment supply. Cobble - boulder bars, sheets and splays are deposited under Newtonian flow conditions from flows with relatively low sediment concentrations. Boulder berms and lobes result from floods with high sediment loads, associated with slope-channel coupling. Flood sedimentation in *lower* reaches of the Tyne comprises vertical accretion of *fine-grained*, well-bedded sediments at overbank and within-channel locations. Larger floods can be identified on the basis of textural discontinuities that reverse the overall fining-upward sequence. Estimation and interpretation of flow magnitude in each setting is complicated by progressive river bed incision over the period of investigation and significant changes in sediment supply which have affected the nature of flood sedimentation.

Trace metal dating of fine-grained, and lichenometric dating of coarse-grained, flood units has enabled detailed and temporally well-defined records of channel and floodplain response to flooding to be established within the Tyne catchment. Since 1600 A.D. fluvial activity at all 3 study reaches has been characterised by alternating periods of river bed incision and stability. Episodic changes in vertical channel stability appear to coincide with non-random decadal-scale fluctuatiions in flood frequency: 3 periods with distinct clustering of large floods (1740-1790, 1860-1899, 1940-1965) were associated with vertical instability (channel trenching) throughout the Tyne basin, while intervening periods with relatively few exceptional floods were associated with channel accretion and floodplain rebuilding in general, but with significant upstream/downstream variation. Distinct clustering in the timing of large floods correspond with short-term hydroclimate changes associated with fluctuations in the configuration of the upper atmosphere. These findings have significant implications for longer-term fluvial development and interpretaion of Holocene alluvial sequences.

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Chapter 1

INTRODUCTION

Research objectives

Long-term records of flood frequency and magnitude are an essential pre-requisite for effective management of river systems in general, and in particular for flood hazard alleviation and hydraulic structure design. Available gauged discharge records, however, are generally limited both in length and geographic distribution, making the magnitude and frequency of large floods difficult to assess. To improve flood analysis hydrologists have conventionally turned to streamflow synthesis from rainfall-runoff models (Anderson and Burt, 1985), regional amalgamation, and documented and monumental historical records (Potter, 1978; McEwen, 1987) to extend the flood database.

An alternative, and arguably more appropriate, means for extending flood series beyond the period of instrumentation is the sedimentary and morphological record of large floods in river valleys (Costa, 1974; 1978), utilised in the U.S.A. for 20 years. In Europe, although extensive use has been made of documentary sources to extend flood series (e.g. Descamps et al, 1989) geomorphological investigations of floods have generally focussed on the impact of single "extraordinary" events which usually attract attention by virtue of spectacular floodplain erosion and deposition (Acreman, 1983; Brown, 1983; Carling, 1986; Harvey, 1986; McEwen and Werrity, 1988; Newson and Macklin, 1990). No investigation has used the alluvial record to reconstruct flood histories in a major British, or continental European, watershed.

Geomorphological flood reconstruction has an inherent advantage over conventional approaches; investigations are not limited by location and, provided adequate dating control is achieved, can extend over any timescale. Flood-related alluvial sequences also provide a record of the long-term impact of flooding on the landscape and of river channel and catchment response to environmental (climate, land-use) changes. In the future river engineers and planners will need to know considerably more about the effects of changing flood frequency in river basins, particularly the spatial and temporal patterns of river response, as a consequence of climate changes predicted as a result of global warming (Newson and Lewin, 1991).

This thesis examines the morphological and sedimentological flood record of the River Tyne, N.E. England, and has three main objectives:

1) To establish the history of flooding in the Tyne catchment over the last 3-400 years.

2) To determine the magnitude and frequency of geomorphologically "effective" floods.

3) To examine the relationship between climate and land-use change, flood regime and river response.

<u>Choice of the study area</u>

The Tyne (Fig. 1.1) is the ninth largest river system in Britain in terms of drainage area and discharge (Ward, 1981). Variations in relief, geology and land-use provide a range of river regime and flood depositional environments and alluvial sequences typical of those found in upland, piedmont and lowland river valleys elsewhere in Britain are contained in the drainage basin. A range of channel and catchment characteristics facilitate geomorphological palaeoflood study and reconstruction in the Tyne Basin.

The catchment is relatively unmanaged compared to many other British rivers (due to the predominance of relatively low value agricultural land over large areas and restriction of large-scale urban and industrial land-use to the lowest 25 km) and there has been little direct human interference to the river channel. The upper River Rede has been impounded since 1903, but effects only a small proportion of the catchment and its influence does not extend beyond the

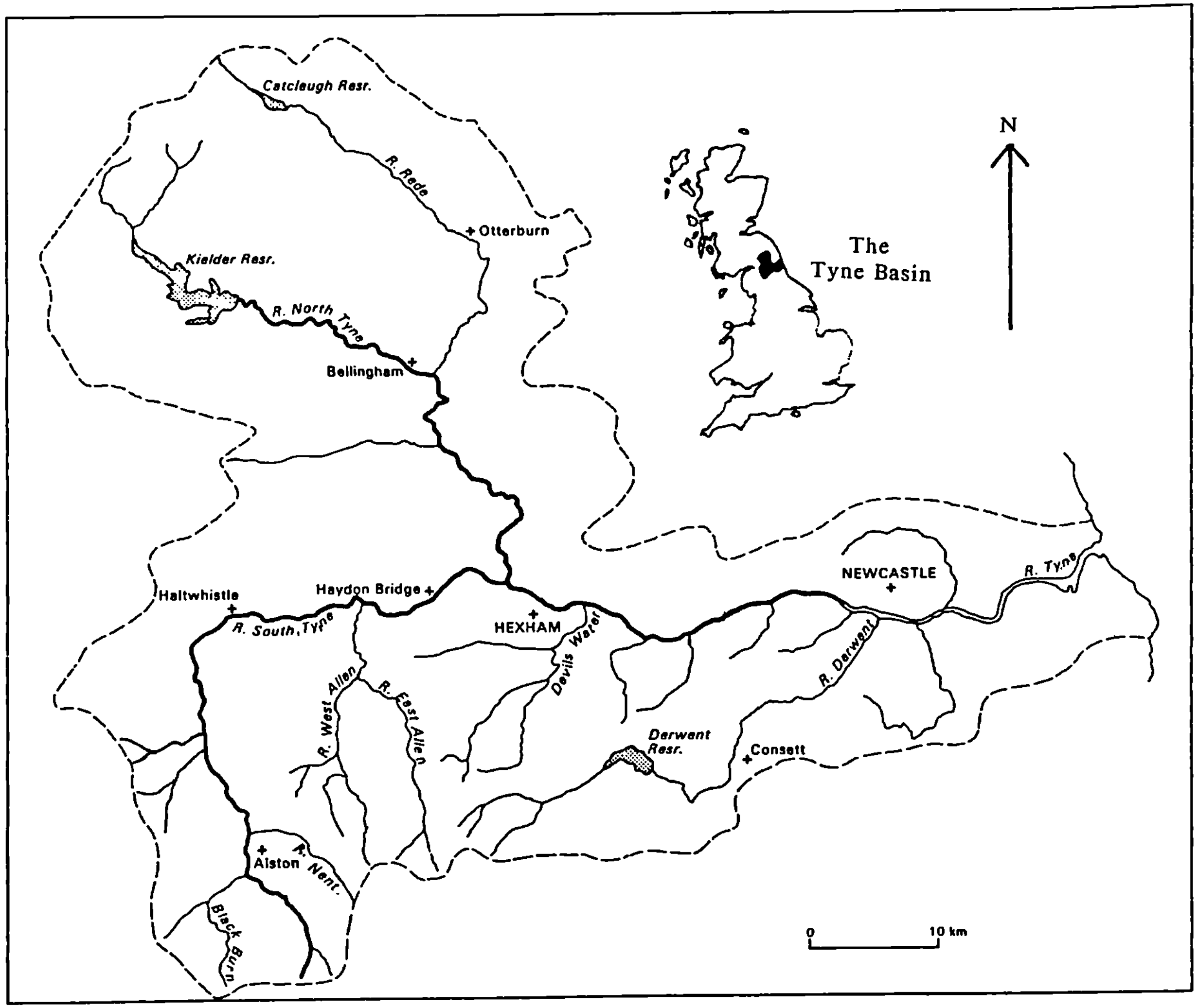


Figure 1.1 Map showing location of the Tyne catchment

Rede/North Tyne confluence. The lack of formal flood protection measures and largely natural flood regime in the Tyne catchment are likely to favour the utility and preservation of sedimentary and morphological flood evidence.

High annual rainfall totals, combined with steep channel gradients that allow a rapid streamflow response to rainfall, result in high stream power and potential for very effective floods (e.g. cases of impressive bedrock erosion recorded in headwater tributaries, Newson and Macklin, 1989). Bedrock, till and alluvial sediment sources in upper part of the catchment have a large sand component and supply abundant material for overbank deposition on floodplains in lower parts of the basin (Macklin and Dowsett, 1989). This offers the possibility of tracing flood units throughout the drainage system.

Comprehensive documentary flood evidence is available for the River Tyne over the last 300-400 years, providing an independent record of flooding with which to compare and calibrate reconstructed geomorphological flood histories.

Research strategy

The scale-dependence of many aspects of channel behaviour (Church, 1980) makes definition of the spatial and temporal context of the study a vital primary consideration. The most appropriate temporal context is the documented period, i.e. the last 400 years. Over this timescale historic flood chronologies are available (e.g. Jones et al, 1984), with which to compare geomorphological-based flood reconstructions, and archive sources provide detailed information on the nature and timing of anthropogenic land-use changes and channel modification. Additionally, given the significant amelioration of temperature from the cold conditions of the Little Ice Age, this a useful period over which to examine the influence of climate change on flood frequency and river behaviour. The most suitable spatial framework in which to assess regime changes and fluvial development over longer-term timescales is that of the river basin (Lewin et al, 1988). The present investigation was based on detailed investigations at representative reaches, that could be integrated to provide a catchment-wide perspective. The overall research programme encompassed 3 main components:

Development of the methodology and techniques for examining and recording flood sediments through detailed case-studies in upland and lowland reaches of the Tyne Basin. Two sites with contrasting alluvial characteristics, in terms of channel gradient, sediment size and stream power, were chosen for study. Firstly, Low Prudhoe in the lower Tyne valley (Fig. 1.1), a lowland, low gradient (0.001 m m^{-1}) reach within a wide valley floor and vertical accretion of fine-grained (suspended) sediment. Secondly, Thinhope Burn, a steep (0.01 m m^{-1}) headwater tributary of the South Tyne (Fig. 1.1), with limited floodplain development, ample availability of cobble and boulder calibre sediment, and high stream power. Flood sediments at each site are described and dated. Reconstructed flood frequencies are then compared with the documentary record to examine local and upstream factors influencing the sedimentary flood record.

Application of the methodology to examine the history and nature of flooding at Broomhaugh Island a piedmont reach in the middle Tyne valley (Fig. 1.1). The piedmont is the major area of sediment transfer between upland sources area and downstream depositional sink (cf. Schumm, 1977), and thus vital for integrating upland and lowland flood records. High rates of fluvial activity in the middle Tyne provide complex geomorphological settings with deposition both of coarse cobble and gravel flood sediments and fine grained suspended load, requiring a combination of the methods developed in the case study reaches.

Integration of individual flood histories to provide a complete overview of temporal trends in flooding on the River Tyne over the last 400 years. Spatial variations in the timing and nature of response to floods on the Tyne and the "sensitivity" of various catchment locations are examined and the controls on flooding at local and catchment scales. Finally, the relationships between climate, flooding and river response are discussed in the context of longer-term alluvial development.

After a review of previous flood-related research in chapter 2 and background information on the Tyne catchment in chapter 3, subsequent chapters are based around the framework outlined above. Chapters 4 and 5 present detailed flood histories for sites in the lower Tyne valley and upper South Tyne respectively. The results of investigations in the middle Tyne valley are reported in chapter 6 and finally chapter 7 provides an overview of the research.

Chapter 2

REVIEW OF LITERATURE

This chapter reviews geomorphological approaches to flood study in the context of the evolution of flood research in Britain and ongoing debates over the role of floods in fluvial geomorphology, and the relative importance of climate and land-use as controls on long-term alluvial development.

Introduction

In Britain the scientific study of floods first developed in the late nineteenth and early twentieth centuries as a response to damage of property and loss of life from a series of dam failures (Newson, 1989). In this context floods were primarily considered as a hazard and research was largely aimed at alleviating the hazard through improved flood prediction. The concept of the "design flood" was devised by engineering and statistical hydrologists for planning purposes, based on relatively simple predictive flood magnitude relationships. A particularly far-reaching and influential report, published by the Institute of Civil Engineers in 1933, provided a series of formulae for predicting peak flood discharge from catchment area, and suggested a "normal maximum flood" for upland catchments based on an envelope curve of known large floods. The report was widely adopted and formed the framework for flood prediction in Britain for the next 30 years (Penning-Rowsell et al, 1986; Wolf, 1966).

Flood frequency analysis

Flood frequency analysis, the procedure for predicting the frequency of occurrence of floods of a given magnitude, developed rapidly in the 1950s particularly after Gumbel's work on the probability distributions of extreme events

(Gumbel, 1941; 1958). Flood frequency analysis assumes floods are drawn from an underlying probability distribution that is continuous and once the appropriate distribution is defined a series of flow records can be extrapolated and the size of the 50, 100 or 1000 year flood identified (Beven and Carling, 1989). The importance of flood frequency analysis in providing the underlying rationale for the majority of flood research in Britain until the late 1960s is exemplified by a quote from Howe et al (1967) that *"the history of the study of floods is essentially the record of a search for adequate tools to analyse past hydrological events in terms of future possibility of occurrence."*

Towards the end of the 1960s, however, there was a growing dissatisfaction with the procedures available for predicting high magnitude floods. A series of large floods had exceeded the "normal maximum flood" envelope curve defined by the Institute of Civil Engineers and there had been significant developments in a number of other areas. A large increase in the number of flow gauging stations, brought about under the River Boards Act (1948) and the Water Resources Act (1963) resulted in a rapid expansion in the hydrological data base, and advances in computer technology made available a wide range of sophisticated analytical techniques. Additionally, increased attention was focussed on the flood hazard in 1968 as a result of extensive flooding in Southern Britain (Newson, 1975) and this provided the immediate catalyst for a major initiative by the Institution of Civil Engineers and the Natural Environment Research Council (N.E.R.C.) at the Institute of Hydrology to collate all available flood data and to modify and update methods of flood estimation. This study culminated in the publication of the five volume Flood Studies Report in 1975 (N.E.R.C., 1975). The report supplied two main methods of obtaining estimates of the design flood: the conventional stochastic approach of flood frequency analysis and a deterministic approach involving unit hydrograph analysis and flood synthesis (Sutcliffe, 1978).

Subsequent to the Flood Studies Report research by engineers and hydrologists expanded in a number of areas. Advances in computing facilitated the development and use of flood routing models involving complex mathematical modelling of river flows (Penning-Roswell et al 1986). Qualitative models were used to investigate the relationships between overbank flow and inundation levels (Price, 1977) and floodplain topography (Lewin and Hughes, 1980). A series of supplements to the Flood Studies Report provided modifications to the main predictive equations reflecting concerns over the applicability of regional multiplication factors and growth curves and the difficulties of flood estimation in small, ungauged catchments (Beven, 1981).

Notwithstanding the increased sophistication of flood frequency procedures since the 1970s, the reliability of the technique is still determined by the length of flow record available; longer flow records provide more reliable flood estimates. The short length of river flow records for many British catchments is therefore a major problem: the average length of gauging station record was calculated to be 12 years in 1975 (N.E.R.C. 1975), and rarely exceeded 40 years. This situation is, to a large extent, due to the lack of statutory requirement to collect runoff records before the River Boards Act in 1948, and in fact most gauges were not actually emplaced until after the Water Resources Act in 1963 (Thornes, 1983). Several long-term systematic flow records do exist, but they are largely confined to lowland reaches within large river systems such as the Thames at Teddington Lock which has been gauged since 1883; smaller basins and upland rivers are still poorly represented by gauging stations. The paucity of flow data is not limited to Britain: in the United States the average length of record in 1986 was 22 years (Kirby and Moss, 1987), largely limited to gauging stations in well populated areas.

To reiterate; spatial and temporal limitations in the availability of flow data pose major problems for flood frequency analysis. Large floods often fall outside the range of observed events and have to be treated as outliers in statistical flood analysis (Costa, 1978) so that their true recurrence interval is very difficult to assess. In order to improve frequency estimates a number of methods have conventionally been used to augment and extend flood series and these are outlined in the next section.

Conventional methods of extending flood series

The two main approaches, hydrological regression on correlated rainfall and streamflow sequences and regional flood estimation, are described in detail by Hosking and Wallis (1986). Despite favourable reports (e.g. Hirsch, 1979) there has been only limited adoption of the first method in Britain. One example is Howe, Slaymaker and Harding's study of floods on the upper Wye and Severn Rivers, in which short flood records were extended through regression on longer flow records from nearby rivers (Howe et al, 1967). Also McEwen (1987) used long-term rainfall data to extend flow records and to check a reconstructed flood series for the Upper Dee, Aberdeenshire.

The second approach, regional flood estimation, is recommended in the Flood Studies Report and widely applied in Britain and North America (Kirby and Moss, 1987; Thomas, 1987). In both countries the Index Flood Method described by Dalrymple (1960) is the most common technique: the flood frequency curve is expressed as a product of the mean annual flood at a specific site and a dimensionless regional frequency curve. Estimation of the mean annual flood (M.A.F.) is crucial and is obtained statistically from peaks-over-threshold or annual-maximum-series of flow data. For ungauged sites estimation of the M.A.F. is more problematic, and can be obtained through regression on catchment characteristics following Flood Studies Report procedures (Sutcliffe, 1978). Recently a number of studies have highlighted several problem areas, particularly regarding the application of the equations in small catchments (N.E.R.C., 1978), suggesting that regional growth/frequency curves may over-estimate the recurrence interval of high magnitude floods in upland areas (Stevens and Lynn, 1978).

Both hydrological regression and regionalisation methods rely on statistical manipulation of data to extend flood series. Clearly more information on the actual frequency and magnitude of past large floods is needed to improve flood frequency analysis, especially in small catchments, the uplands and other problematic areas. In this context the next section will review the use of documented historic flood information to reconstruct and extend flood series.

Documentary flood information and historic flood chronologies

Historic flood data, defined as the human record of flood peaks that occurred before the time of systematic hydrological recording (Stedinger and Baker, 1981), has a long tradition of use in flood frequency analysis (e.g. Benson, 1960). In the U.S.A. official agencies such as the U.S. Water Resource Council routinely incorporate historic information in their analysis (Thomas, 1985) and in Britain the use of historic data was advocated in the Flood Studies Report.

There are various sources of historic flood data. Many water organisations (e.g. the privatised water companies and National Rivers Authority) have files of flood information for the pre-gauging era in the twentieth century and there are a number of reviews and compilations of large British flood events (e.g. Acreman, 1989; Brookes and Glasspole, 1928; Newson, 1975; Rodda et al, 1976). Information on floods occurring before this century can be obtained from a variety of indirect sources, summarised by Potter (1978), Hooke and Kain (1982) and McEwen (1987). For nineteenth century events books and journals (especially meteorological publications), newspapers, floodmarks and lock gauge boards are the main sources of information. Prior to 1800, estate records and weather chronologies can provide documentary evidence of floods.

The type of information obtained from historic sources varies greatly in quality and reliability and much is of a descriptive nature (McEwen, 1987). In particular, newspaper accounts are concerned with reporting the flood hazard, so often relate to the effects of floods on lives and property rather than provide specific hydrological details (Thornes 1983). However valuable information can be obtained on flood discharge (stage or relative magnitude), timing (period of inundation, rate of recession), geomorphic effects and antecedent conditions (meteorological and fluvial).

For flood frequency analysis data on flood discharge and timing are the main requirements. The form of discharge information available from documented sources falls into two categories; either the actual magnitude of flood peaks is known or, more commonly, only threshold exceedance information is available such as a list of flood peaks over a particular level. This latter case constitutes a "censored" sample in statistical terms (Leese, 1973; Stedinger and Cohn, 1986) and is generally incorporated in frequency analysis using a weighted moments procedure (e.g. Wall et al, 1987), although more recently a maximum likelihood approach has been recommended by Condie and Lee (1982) and Stedinger and Cohn (1986) on the basis that its greater reliability and robustness allows a wide variety of information to be used.

A recent study by Acreman and Horrocks (1990) illustrates the utility of incorporating historical information in frequency analysis. Floods on the River Kenwyn, Cornwall in January and October 1988 were calculated to have return periods of 350 and greater than 350 years using conventional methodology (Flood Studies approach). These estimates were based on extrapolation from gauged records of under 20 years in length. The 1988 floods were "outliers" considerably larger than any other measured flows making it very difficult to find an appropriate flood distribution to fit the data. Subsequent re-analysis incorporating historical threshold exceedance data provided extra data points enabling a more accurate distribution to be fitted and modifying return period estimates to 50 and 100 years respectively.

Historic flood data has been used in the reconstruction of long-term flood chronologies for several rivers in Britain. Howe et al (1967) extended the flood records of the Upper Wye and Severn Rivers back to c.1700 using historic records, and McEwen has established flood chronologies for a number of rivers in Scotland extending over periods of 2-300 years (e.g. McEwen, 1990). Information on flood seasonality and hydrometeorological conditions, as well as magnitude and frequency, provided by such chronologies have been used in a number of studies to examine the influence of climate and land-use on flooding (e.g. McEwen, 1989).

Limitations

The utility of historic flood information is limited by problems concerning the completeness of the record, accuracy and reliability of measurements and non-stationarity.

Documentary records of flood events are non-systematic and non-continuous in space and time. As historical records consist of human documentation of floods they are limited spatially to areas where people are present to observe and record the event. There is therefore a bias towards populated/urban and lowland reaches where riverside land is more intensively used and valued at a higher premium. For example Howe et al (1967) found more complete and longer flood records for larger towns on the middle Severn and Wye compared to remote, upland reaches. Temporally the amount and reliability of historical flood data decreases with years before present (Sutcliffe, 1987). Records are generally considered to be comprehensive to 1750 (Archer, 1987; McEwen, 1990) and only discontinuous prior to this. Cross-checking with a range of sources, although time consuming, increases the reliability and comprehensiveness of the sample.

Much information on floods is descriptive in nature (McEwen, 1987) and often relates to damage of land or property rather than providing level or discharge data. Where the latter is available then the accuracy of measurement should be considered as instrumentation was more rudimentary in the past, and prior to the twentieth century most observations were done by non-hydrologists. Stage information rarely relates to present gauging stations and covers a variety of locations, so there are difficulties in assessing discharge and comparing floods. Archer (1987) suggests transferring information to reference sites but this is likely to produce added errors and complications to the data.

Natural and anthropogenic river channel and catchment changes can alter stage-discharge and rainfall-runoff relationships and introduce non-stationarity into flood series. Anthropogenic influence is especially important in urban areas. For example, the building of bridges, mills and other river structures affects the river level during floods by causing ponding upstream. Archer (1987) showed that the River Wear at Durham had been affected by urbanisation, flood embankments and reservoir construction in the catchment but found it difficult to quantify the effects of each change. The geological stability of a site is also an important consideration (Sutcliffe, 1987). Channel incision or aggradation will affect level measurements as well as the discharge required to overtop banks and flood land. It is therefore vital to know in some detail the history of river behaviour at a reach and catchment scale when compiling or using a documentary record of flood events.

An alternative long-term record of flooding is provided by the alluvial sediments and landforms within a river basin. These represent river response to past floods and thus also provide valuable information on alluvial history. The following section reviews the development, application and utility of geomorphological approaches to flood reconstruction.

Geomorphological flood histories

The use of alluvial stratigraphy in flood analysis originated and developed in the United States, where there is a long tradition of research on paleoflood geomorphology (Costa, 1986), dating to the 1930s. Two of the first systematic investigations of flood sediments, made by Grover (1937) and Jahns (1947), discussed the similarity between contemporary flood sediments and older deposits identified in the alluvial record, commenting on the potential utility of the latter to flood frequency analysis, although no direct application was undertaken. A proliferation of studies in the 1950s and 1960s, largely undertaken under the auspices of the United States Geological Survey (U.S.G.S.), reported on the geomorphological characteristics of sediments and landforms resulting from recent high magnitude floods and provided a comprehensive review of flood erosion and deposition in a range of environments. Work included detailed investigation of the alluvial stratigraphic record left by individual events (McKee et al, 1967), the spatial distribution and nature of coarse-grained flood deposits (Bull, 1942) and description of major erosional and depositional features (Scott and Gravlee, 1968; Stewart and LaMarch, 1967; Wolman and Eiler, 1958). These studies provided a good basis for the subsequent identification and investigation of palaeoflood sediments and landforms. Additionally a limited number of *ad hoc* soil and vegetation-based investigations related specific floodplain properties to damage by past floods and frequency of flood inundation (e.g. Helley and LaMarche, 1973; Sigafoos, 1964).

In 1974 a review paper by Costa brought together much of the preceding work to provide a coherent summary of the stratigraphic, morphological and pedologic evidence for large floods. The paper anticipated the use of geomorphological evidence in formal flood prediction procedures, and following the development of the appropriate statistical techniques to allow incorporation of such data in frequency analysis, Costa used the geomorphic approach to modify return period estimates of recent catastrophic floods in the U.S.A. (Costa, 1978).

Geomorphological palaeoflood studies subsequently developed in two broad areas, based on work in bedrock and alluvial systems. Baker and co-workers investigated large floods and channel response (Baker, 1973; 1975; 1977; Baker and Ritter, 1975; Ritter, 1975) and slackwater sedimentation (Patton, 1977; Kochel and Baker, 1982; Baker, 1983; Baker et al, 1983) in bedrock fluvial systems largely located in southwest U.S.A. Reconstruction of flood histories over several thousand years has been attempted through the study of slackwater sediments deposited by very high magnitude (and rare) events on a number of rivers in the U.S. and Australia (e.g. Partridge and Baker, 1987; Baker and Kochel, 1988; Kochel and Baker, 1988; Pain, 1988; Webb et al, 1988). Sophisticated statistical techniques have been developed to facilitate the incorporation of slackwater palaeoflood information in flood frequency analyses (e.g. Stedinger and Baker, 1987; Stedinger et al. 1988). Application of slackwater techniques is limited outside of bedrock fluvial systems due to the necessity for a stable channel cross-section, otherwise changing stage-discharge relationships make the reconstruction of flood magnitude difficult.

The other major area of geomorphological palaeoflood research has been concerned with reconstructing floods on alluvial streams in humid areas of the U.S. in the context of elucidating channel response to climatic and anthropogenic changes (Brackenridge, 1988; Knox, 1977; 1985; 1987a). Stratigraphic evidence of large floods in alluvial river basins generally in the form of textural reversals in fining-upward sequences of alluvial sediments (Knox, 1987b). In contrast to slackwater studies, this research and has not been applied in the context of frequency analysis.

An important advantage of using alluvial stratigraphy to reconstruct flood histories, in addition to purely documentary evidence, is that it can be applied in areas (such as sparsely populated uplands) where conventional flood information is most inadequate. However, to date, there have been few applications outside the areas cited above, and none in a British river basin.

Flood geomorphology in Britain

The subject of flood geomorphology developed late in Britain compared to the United States, as a result of the prevailing influence of the hydrological-engineering-statistical approach to flood study. The catastrophic Lynmouth flood of 1952 (Delderfield, 1953) was the first in Britain to receive widespread attention from geomorphologists as well as hydrologists and engineers (Dobbie and Wolf, 1953; Green, 1955). However it was only after a proliferation of research in fluvial geomorphology in general during the 1970s and 1980s that geomorphological aspects of flooding began to be studied in detail. Over the last 20 years there have been 2 main areas of flood research, based on work in upland and lowland river basins.

Studies of floods in lowland catchments have focussed on measurement of the processes and amount of suspended sediment transport during contemporary large events (Lambert and Walling, 1988) and rates of overbank fine-sediment deposition (Brown, 1987: Lambert and Walling, 1987). Longer term studies comprise general Holocene alluvial histories, largely within an archaeological context relating alluviation to anthropogenic disturbance and natural causes (e.g. Brown, 1983; 1987; Brown and Barber, 1985; Burrin and Scaife, 1984; Lewin et al, 1983; Macklin, 1985; Robinson and Lambrick, 1984). No studies have attempted to relate ancient flood sediments to specific large floods.

There have been more geomorphological studies of floods in upland Britain compared to lowland, with the emphasis predominantly on flood effectiveness, reflecting the greater likelihood of catastrophic events in such areas; increased incidence of heavy rainfall, steep valleys and small catchments (Newson, 1989). A large number of case studies published in the 1980s reported sedimentological and geomorphological effects of high magnitude events and estimations of discharge (e.g. Carling, 1989; Coxon et al, 1989; Harvey, 1986; Harvey and Wells, 1987; Hitchcock, 1977; McEwen and Werritty, 1988). Anderson and Calver (1977) considered recovery time and persistence of flood features, and following papers on flood effectiveness by Wolman and Gerson (1978) and Newson (1980) an increasing volume of work focussed on effectiveness, especially regarding the relationships between flood frequency and channel adjustment in relation to thresholds (Harvey et al, 1982; Thompson, 1987; Newson and Macklin, 1990). Over longer timescales studies of Holocene valley development in the uplands have dealt with alluvial fan and gully sediments along with alluvial river terrace deposits (Harvey et al, 1983; Harvey et al, 1984; Harvey and Renwick, 1987; Hooke et al, 1990; Macklin and Lewin, 1986; Richards, 1981; Richards et al, 1987). The relationship between high magnitude events and channel and floodplain development has been examined over timescales of several hundred years (Macklin, 1986; Werritty and Ferguson, 1980) and c.150 years (Hooke and Redmond, 1989). Only one published study has attempted to reconstruct specific palaeoflood parameters from geomorphic evidence, that is Carling and Glaister's (1987) investigation of boulder berm deposits associated with the 1927 dambreak flood in Glenridding Beck, Cumbria.

The limited application of alluvial stratigraphy to reconstruct flood histories and augment flood frequency data outside the U.S.A., and a lack of palaeoflood studies *per se*, is largely a consequence of continued debate over the role of floods in fluvial geomorphology, river channel and catchment behaviour in response to flood frequency changes and the roles and relative importance of climate and land-use. The history and current status of these debates are reviewed in subsequent sections.

Floods in fluvial geomorphology

The statement of Lewin (1989) that *"the role of floods in geomorphology has long been...persistently controversial"* exemplifies a long-standing argument over the role and relative importance of floods in fluvial systems that is part of a general debate regarding the work or effectiveness of events of different magnitudes: the relative contribution of infrequent high magnitude events (such as floods) compared to the cumulative effect of frequent small magnitude events in their ability to shape the landscape (Kochel, 1989; Lewin, 1989).

Baker (1988) suggests that this debate has its roots in the opposing seventeenth and eighteenth century view of the landscape as being formed by catastrophic events against the nineteenth century concept of uniformitarianism. In the former, catastrophist, view extreme events were thought to be of primary importance to landscape evolution and rare, large floods as exemplified by the biblical deluge played a central role in this argument. The alternative uniformitarian view considered that landforms are the product of present-day processes operating *slowly* over *long periods*, consequently the role of extreme events was minimalised. Uniformitarianism has continued to dominate scientific thought in the twentieth century.

After 1950, the development of "modern" geomorphology, based on quantitative process measurements (Werritty, 1989), necessarily emphasised the role of frequent small magnitude events as they were measurable and accessible within the bounds of short-term research projects. The logistical difficulties associated with direct measurement of large infrequent floods has accentuated the problem of assessing their role in fluvial geomorphology (Baker and Costa, 1987). Throughout the 1960s and 1970s the "fluvial process" school (cf. Lewin, 1989) arising from the work of Leopold, Wolman and Miller (e.g. Leopold et al, 1964) was predominant in fluvial geomorphology. Process studies on a number of alluvial streams in the U.S.A. led Wolman and Miller (1960) to quantify the relative importance of high magnitude infrequent events against more frequent lower magnitude events in terms of "work" done on the landscape by the amount of suspended sediment transported. They concluded that the biggest proportion of total load was carried by flows which occur once or twice a year, and 90 % of sediment was moved by event occurring approximately every five years. Higher magnitude events were considered to be less important as regards "work" done because of their infrequency of occurrence.

Within this framework it was widely accepted that river channels were generally adjusted to frequent and hydrologically identifiable events. Paleohydrological studies concentrated on relating the "dominant" or "formative" discharge with specific channel characteristics (see Gregory, 1983). Dury's (1961; 1976) "channel-forming" discharge with a recurrence interval of 1.58 years was widely used in sedimentological reconstructions of former channels (Miall, 1978). The "fluvial process" approach utilised the concept of a graded stream (Mackin, 1948; Knox 1975) in which channels were considered to develop a stable morphology based on prevailing discharge and sediment load characteristics, under "normal" flow conditions.

As a result of the general acceptance of this approach the study of large floods became somewhat neglected. Most research consisted of short-term process studies monitoring river discharge and sediment load. The rarity of floods made them difficult subjects of study and they were usually regarded as anomalies within an otherwise orderly and logical fluvial system.

The work of Schumm and others during the 1970s, however, challenged this orderly view of fluvial geomorphology, and led to a re-assessment of the role of floods. Schumm applied a systems approach to river basins, considering them as an *"open process-response system in a condition of dynamic metastable equilibrium"*. The concepts of threshold change and complex response (Schumm, 1973; 1975) were widely taken up in fluvial geomorphology (Newson, in press). In this context it was recognised that major modification to fluvial systems can occur when threshold conditions are exceeded; and on many rivers only rare, large floods bring about threshold changes and thresholds may not be passed during low magnitude floods, regardless of how frequently they occur (Kochel, 1988). Consequently the concept of threshold behaviour of fluvial systems re-affirmed the significance of large discharge events and renewed interest in flood studies. At a wider level Hart (1986) has suggested that the development of threshold concepts in geomorphology indicates a return to the pre-nineteenth century catastrophist viewpoint.

A large number of case studies of floods in a variety of environments (e.g. Anderson and Calver, 1977; 1980; Harvey, 1984; Newson, 1980; Gupta, 1983; McEwen and Werritty, 1984; Nolan and Marron, 1985; Nanson, 1986) demonstrated the widely varying channel response to floods, indicating that some environments are more prone, or more sensitive, to long lasting landform modification by floods (Brunsden and Thornes, 1979).

An alternative definition of fluvial work developed from the concepts of threshold change and landscape sensitivity is flood effectiveness (Wolman and Gerson, 1978; Newson, 1980) which concerns channel response and recovery time. Throughout the 1980s effectiveness studies dominated flood research in fluvial geomorphology and continue to be important (e.g. Newson and Macklin, 1990). Furthermore, preoccupation with frequency and magnitude considerations in all realms of geomorphology has ensured that flood research now occupies a central position in the discipline. This is well illustrated by the recent publication of three significant conference volumes devoted to flood geomorphology (Mayer and Nash, 1987; Baker et al, 1988; Beven and Carling, 1989).

Recovery time and the temporal spacing of events are of key importance to the understanding of effectiveness. Geomorphologically-based flood histories can provide information on the long-term impact of flooding on the landscape and therefore make a valuable contribution to the debate over the role of floods in fluvial geomorphology.

Floods and climate

One of the first studies to examine the relationship between floods and climate was undertaken by Hoyt and Langbein (1942) who investigated 33 years of streamflow and meteorological records for the United States and Canada. Trends in the timing of flow extremes (i.e. floods and droughts) were found to be widespread over a range of geographic regions and showed close correspondence to prevailing meteorological conditions. A detailed study of long term streamflow and weather records for the Upper Mississippi Valley by Knox et al (1975) examined the linkages between flood characteristics and climate in more detail. Flood magnitude and frequency were found to be highly sensitive to variations in seasonal precipitation brought about by shifts in large scale hemispheric circulation patterns. The recurrence interval of high magnitude events showed a particularly close relationship.

There have been few long-term studies of flood hydroclimate in Britain. McEwen (1989) looked at major floods on the River Tweed, Scotland over a 100 year period and identified a close correspondence to extreme rainfall events brought about by summer frontal storms and cyclonic storms in autumn, demonstrating the importance of atmospheric circulation patterns in controlling flood occurrence.

Probst (1989) has demonstrated that synchronous fluctuations in discharge for a number of European rivers since 1800 are in phase with European rainfall patterns. Additionally Probst and Tardy (1987) showed that the general patterns were also true for fifty major rivers world-wide: mean annual discharge fluctuations since the beginning of the century are broadly synchronous within continental-size regions. Attenuations and lead-lag phenomena follow the direction of the prevailing weather systems (e.g. west to east in Europe). Comparisons between continents indicated that although runoff trends are often in the opposite direction, the timing of major changes is similar.

Some of the most extreme floods recorded have not been generated by rainstorms but are a result of snowmelt. Snow and ice accumulate over long periods of time and alter the pattern of runoff which would otherwise be determined by the distribution of precipitation. Hence snowmelt floods have very different populations in terms of magnitude/frequency relationships compared to rainstorm events (Church, 1988). Jarret (1980) found major differences between rain and snow flood populations for a number of streams in the Colorado Mountains, U.S.A.. In fact there are likely to be many different types of mixed population floods resulting from both meteorological and hydrological processes. Outside of purely nival areas, rapid snowmelt induced by rain on snow can be an important factor exacerbating flooding and many large floods in Britain have had snowmelt contributions, such as the 1947 floods in the north and east (Newson, 1975).

A series of papers by Hirschboek have examined the effects of long and short-term climate fluctuations on hydrology and floods, demonstrating that climate activity can generate flooding at a variety of scales: small convective rainstorms that produce local flash floods to cyclonic systems affecting major regions (Hirschboek, 1988). However, she concludes that climatic activity operating at a large spatial scale, through the configuration of the upper atmosphere, provides the ultimate framework from which the more immediate causes of flooding are generated (Hirschboek, 1987).

Climate change

Climate changes predicted as a result of global warming over the next 40 years will have a large impact on circulation patterns by altering zonal temperature gradients and hence ultimately a profound affect on river runoff and fluvial systems. Newson and Lewin (1990) have emphasised that major river management problems will result from changes in flood and drought conditions. In Britain government policy is precautionary in that it aims to *"forestall the possible impact of climatic changes resulting from the greenhouse effect"* (M.A.F.F., 1990), i.e. through structural protection measures. Unfortunately prediction of the fluvial response to changes in climate, although fundamental to this approach, is very difficult. The two main problem areas are outlined below.

Firstly predictions of the nature of future climatic change vary widely. Global climate models have produced a range of likely scenarios for future temperature changes which in turn produce a range of precipitation estimates. Even for a given precipitation and temperature situation the precise effect on river runoff is difficult to predict. Modelling undertaken by Palutikov (1987) indicated there would be a general increase in runoff for rivers in northern Britain and a decrease in the south; but once factors such as the direct effects of CO_2 on plant transpiration are taken into account a different and much more complicated situation is predicted.

The second area of difficulty in predicting the nature of likely adjustments results from the complex relationship between changes in runoff and fluvial response. Earlier sections of this review outlined the controversy over the role of floods in fluvial geomorphology, and the ongoing debate over what aspects of river flow most influence river sedimentation, deposition and channel change. There is also a lack of knowledge on the factors governing flood effectiveness and response and recovery time.

The extended record of floods and fluvial response supplied through the study of palaeohydrology and alluvial sedimentary sequences can clearly contribute a great deal in this context by providing an analogue of past response. Climate fluctuations through the Holocene have been of the same order as those predicted as a result of global warming, temperatures have varied by +/- 2°C and precipitation by +/- 10-20 % (Knox, 1983). The warming period following the Little Ice Age, that is the period since c.1750, would appear to be a particularly appropriate area of study. In the United States a number of studies have examined long term changes in runoff and flood magnitude and frequency in response to Holocene and historic climatic changes (e.g. Knox, 1983; 1985; 1988 in the Upper Mississippi Valley and Chatters and Hoover, 1986 in Washington).

A range of mechanisms have been shown to affect river response and/or the sedimentary record of flooding (Brackenridge, 1988; Burrin, 1985) in different situations, complicating the direct relationship with climate. Traditionally, alluvial studies in Britain have emphasised anthropogenic land-use changes, rather than hydroclimate, as the dominant control on river sedimentation (Bell, 1982; Brown and Barber, 1985; Burrin, 1985). However, these studies have largely been undertaken in lowland river basins which have been intensively occupied, and in small catchments where human influence is likely to be proportionately greater. A recent review of published Holocene alluviation studies for a range of river basins throughout Britain found clear patterns in the timing of major changes in channel and floodplain activity and concluded that, although the alluvial record may be modified by man, climate was the principle driving mechanism (Macklin and Lewin, in press).

In addition to anthropogenic influences a number of other factors have also been suggested to modify the relationship between climate, flooding and alluvial sedimentation. Starkel and Thornes (1981) suggest the existence of material thresholds in river basins may promote discontinuous response to changing climatic conditions and result in complex spatial patterns of erosion and deposition. Changes in the amount, size and quality of sediment supplied from upstream, can bring about changes to the mode of action of a river - sedimentation or erosion - which are independent of climate change. Any climatic change that brings about erosion upstream will increase sediment supply to downstream reaches and result in sedimentation. Lagged biogenic response to climate change is a further complicating factor, as vegetation is an important regulator of sediment supply to river channels (Knox, 1972; 1984; McDowell, 1983).

Summary

While a large number of studies over the last 10-20 years have emphasised the significant role of floods in floodplain and valley development and demonstrated the importance of climate as the ultimate control on flooding, there has been continued debate over the roles and relative importance of climate and land-use as causal mechanisms for fluvial activity. To disentangle these relationships a major priority area for reseach, therefore, must be to investigate the precise nature and direction of the linkages between flood frequency and magnitude variations and channel and floodplain adjustment for a range of alluvial settings and at a variety of scales. Geomorphological and sedimentary flood histories, reconstructed in sufficient detail, provide a record of river response to flooding that could potentially enable some of these outstanding questions in fluvial geomorphology to be resolved.

Chapter 3

BACKGROUND TO THE STUDY AREA: THE TYNE BASIN, NORTH EAST ENGLAND

Introduction

The River Tyne is a gravel-bed river with a drainage area of 2927 km^2. It is fed by two major tributaries (Fig. 3.1), the River South Tyne (drainage area 800 km^2) which flows north off the Northern Pennines and the River North Tyne (drainage area 1118 km^2) which flows south from the Northumbrian Fells. The Tyne is tidal to Wylam (NZ 121645), and has mean and maximum recorded discharges of 44 $m^3\ s^{-1}$ and 1497 $m^3\ s^{-1}$ measured at Bywell (NZ 048613).

Geology and physiography of the Tyne basin

The Tyne basin is bounded by upland areas to the north, south and west and is traversed by the Stublick fault system; the Tyne valley and many of the southern tributaries are fault guided (Jarvis, 1977). There is a marked contrast between the modified scarp landscape of the Northumbrian Fells and the plateau-like region of the Northern Pennine block. North of the Tyne valley there are few tributaries apart from the North Tyne itself and scarps lie close to the river. To the south, however, the ground rises through an intermediate hilly zone and tributaries are more numerous and better developed. The upper South Tyne catchment is an area of upland fells and deeply trenched dales. As a consequence of high catchment relief (893 m, Fig. 3.2) and relatively short channel length valley gradients throughout the system are steep (e.g. 0.0019 m m^{-1} in the middle Tyne, 0.001 m m^{-1} in the Lower Tyne valley) but particularly in headwater tributaries of the South Tyne (up to 0.2 m m^{-1}).

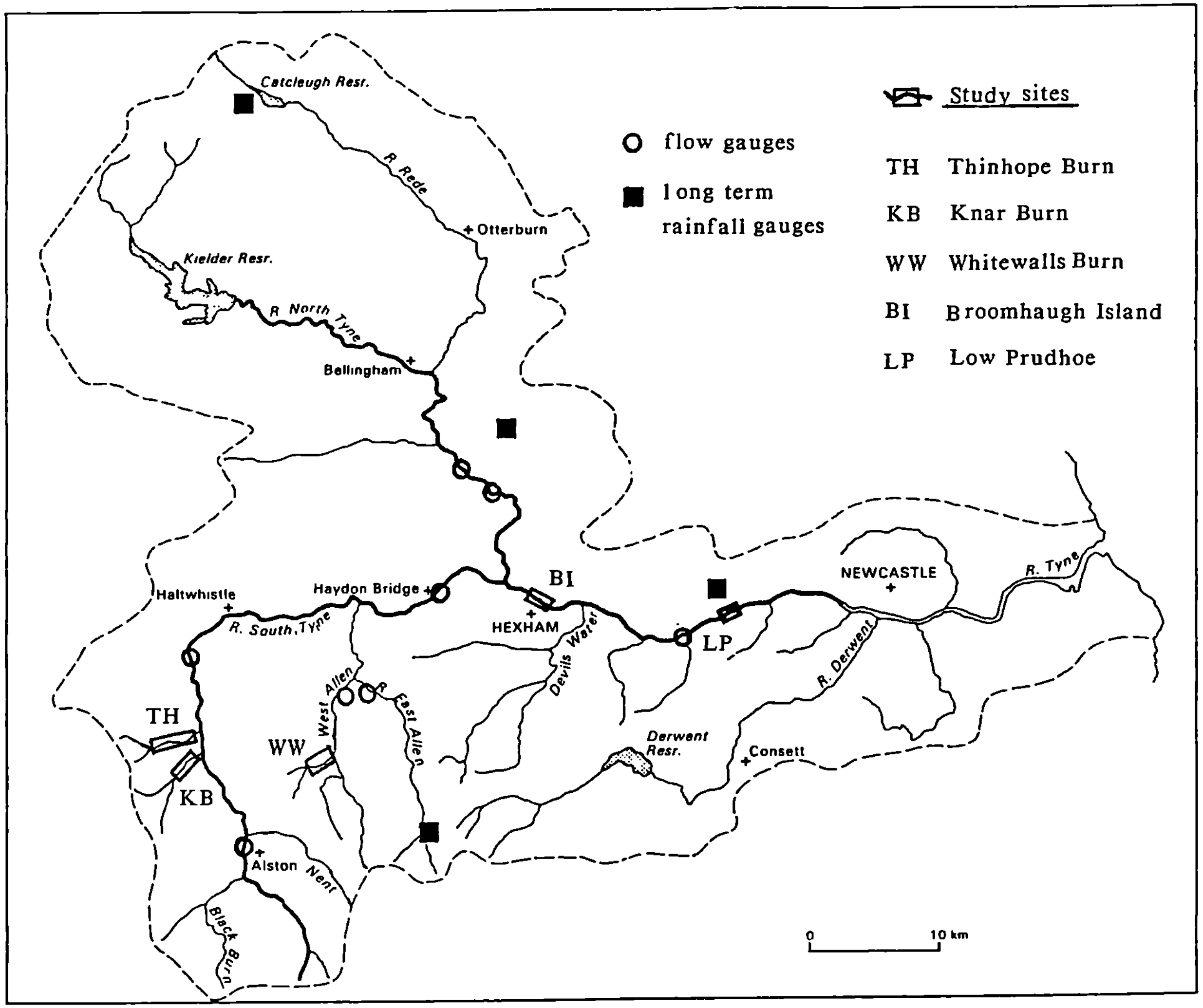


Figure 3.1 Map of the Tyne Basin showing location of the study sites, gauging stations and long-term precipitation records

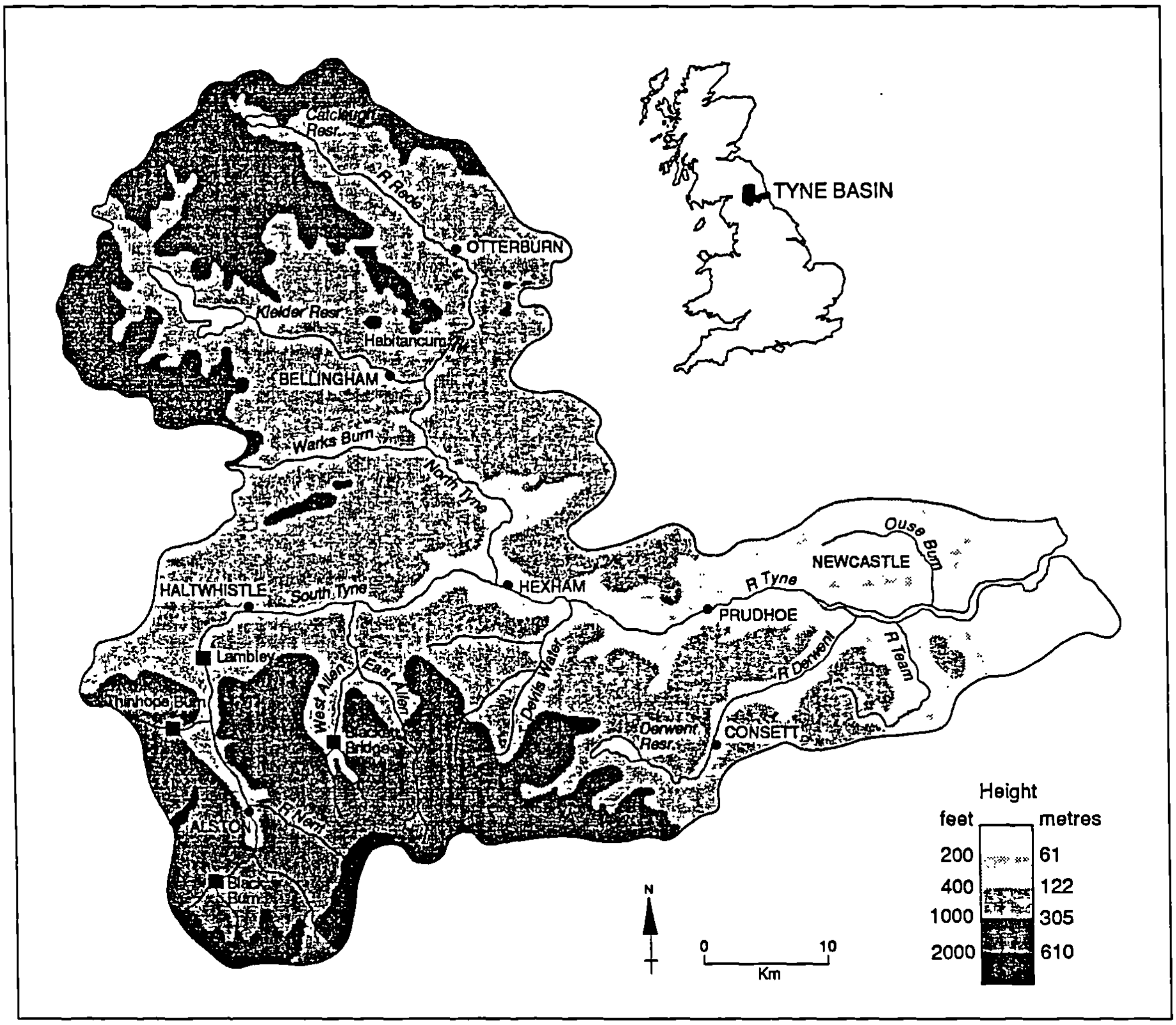


Figure 3.2 Relief map of the Tyne Basin

The catchment is underlain predominantly by Carboniferous sandstones, limestones and shales (Fig. 3.3 and Table 3.1), with outcrops of igneous rocks in the headwaters of the North Tyne (Cheviot granite) and lower reaches of the North and South Tyne (Whin Sill) (Robson, 1965; Eastwood, 1953). Headwater tributaries and lower reaches of the South Tyne drain extensive areas of base-metal mineralisation, associated with the Northern Pennine Orefield (Dunham, 1990).

Glaciogenic sediments from the Late Devensian Dimlington Stadial and earlier Pleistocene glaciations (modified by solifluction processes) cover valley slopes and infill glacially overdeepened valley floors within the Tyne basin. The predominant Devensian ice movement was eastward from the Solway, although both the Cheviot and Northern Pennine upland areas supported ice-caps (Eastwood, 1953; Raistrick, 1931) and many of the glacial and fluvio-glacial deposits in the catchment comprise locally derived material.

Present river channels are largely inset within Pleistocene glacial or fluvio-glacial deposits, Holocene alluvium or bedrock. Contemporary alluvial sedimentation ranges from coarse cobble-gravels in laterally and vertically mobile reaches of the upper North and South Tyne catchments, to fine-grained vertically accreted alluvium in laterally stable reaches of the lower Tyne valley.

<u>Archaeology and land-use history</u>

The early to mid-Holocene settlement and land-use history of the Tyne Basin is not known in great detail, especially for the Northern Pennine areas. Mesolithic and Neolithic occupation appears to have been restricted to valley floors and lower valley slopes of the lower Tyne (particularly the Hexham-Corbridge area), North Tyne and Rede (Weyman, 1984; Jobey, 1977; 1978). Pollen evidence suggests only localised and limited forest clearance (Turner and Hodgson, 1983). During the Bronze age river valley sites continued to be important (Higham, 1986) although there was some expansion of settlements at higher altitudes (Burgess, 1984). The first firm indication of forest clearance dates to the middle of the second

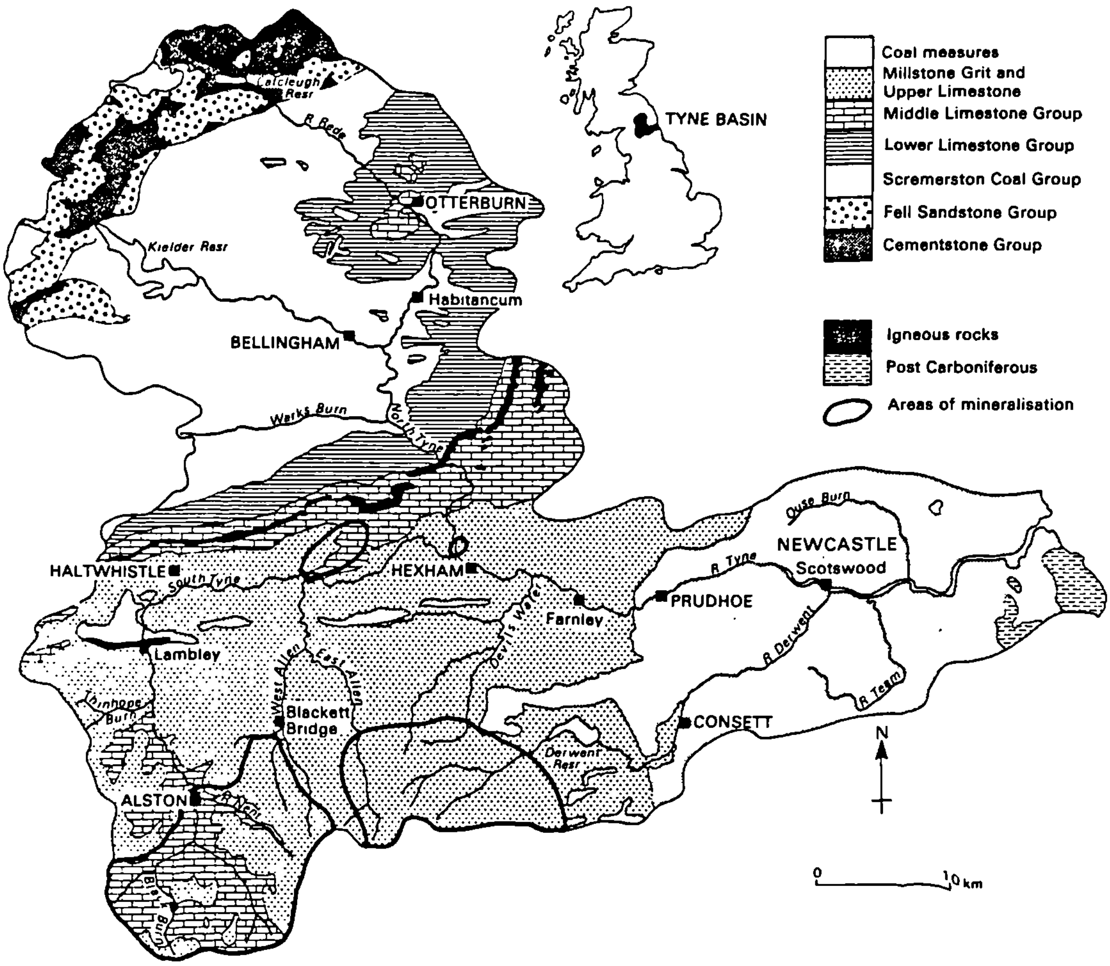


Figure 3.3 Geology map of the Tyne Basin

North Tyne (Reaver Hill)		South Tyne (Haydon Bridge)		Lower Tyne (Bywell)	
	%		%		%
Screm coal	61	MG & UL	67	MG & UL	37
Lower lst	20	Middle lst	23	Screm coal	28
Fell sst	10	Others	10	Middle lst	14
Others	9			Lower lst	11
				Others	10

<u>Key to abbreviations</u>

Screm	Scremeston
lst	Limestone
sst	Sandstone
MG	Millstone grit
UL	Upper limestone

<u>Table 3.1</u> Summary table of the main geologies of the South Tyne, North Tyne and Lower Tyne catchments

millenium B.C. in Tyndale and Redesdale (small-scale clearance and evidence of pastoral and arable agriculture at Steng Moss in the Rede valley around 1644 B.C., Turner, 1979) although work in the Northern Pennines indicates that these areas were still well forested at this time (Turner, 1979). Expansion of settlement during the Iron Age and Romano-British period, however, appears to have been associated with widespread and permanent forest clearance and increasing importance of cereal cultivation.

Pollen evidence suggests that cleared woodland areas were maintained for a short time after the Roman withdrawal (Davies and Turner, 1979), but settlement in marginal areas was soon abandoned (Jobey, 1977) and forest re-generation had occurred by c.1000 A.D.. By the late thirteenth century settlement had been consolidated in enclosed villages on lower valley slopes in the South Tyne as well as the North and lower Tyne valleys (Newman and Harbottle, 1973) and there were large areas of cleared land (Davies and Turner, 1979).

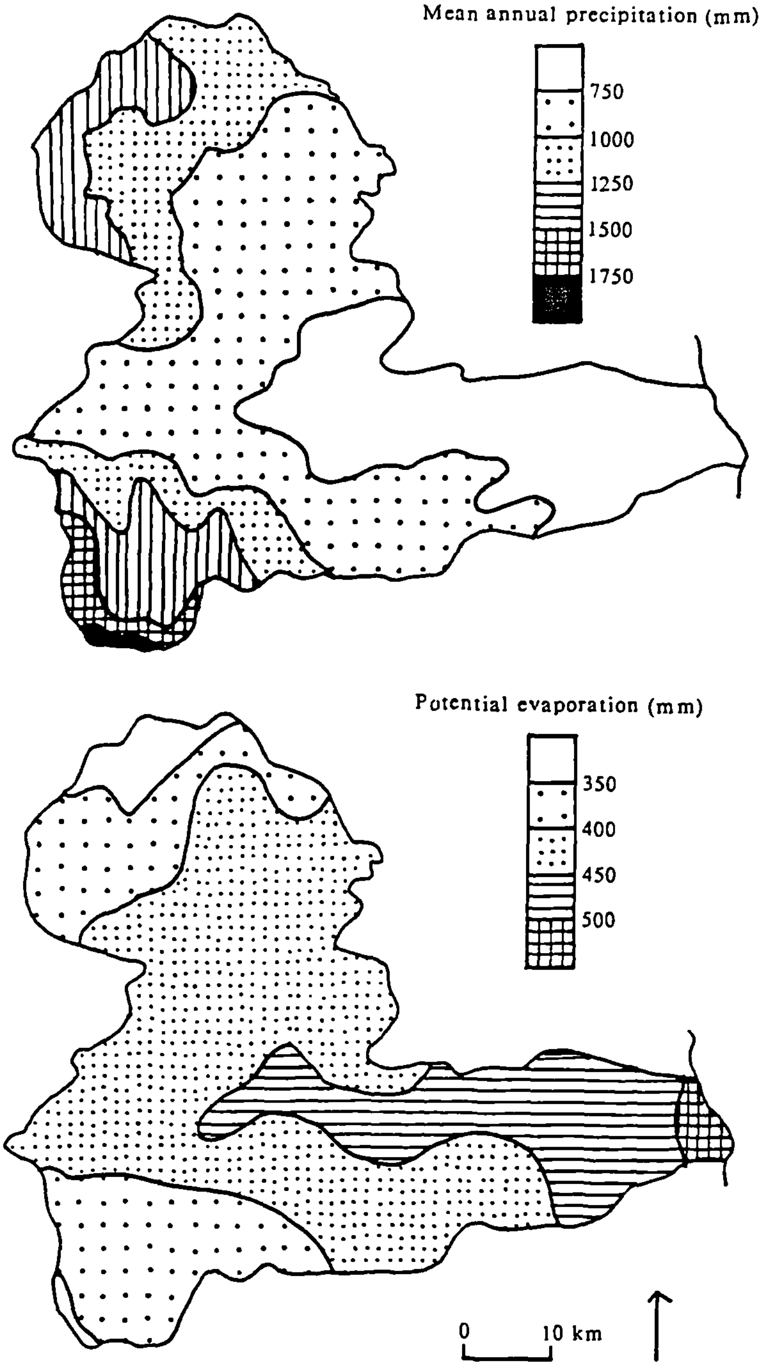
Widespread depopulation and abandonment of settlements occurred in the fourteenth century (Jobey, 1977). The fifthteenth and sixteenth centuries saw a (short-lived) peak in settlement in the North Tyne and Rede valleys (Harbottle and Newman, 1977), on a scale not reached since; many permanent farms established during the seventeenth and eighteenth centuries appear to have been abandoned during the Little Ice Age climatic deterioration. In the South Tyne valley there was an influx of population during the nineteenth century, associated with lead mining in the Northern Pennines, resulting in significant agricultural expansion and land enclosure (Wallace, 1890). A marked and prolonged decline in population began in the late nineteenth century.

There is a long history base-metal mining in the South Tyne and it's major tributaries (the Rivers Nent and Allen), dating to Roman times at least (Raistrick and Jennings, 1965). Early mining undertakings were generally small-scale and isolated. Rapid technological developments in the early part of the seventeenth century, however, enabled deeper and more extensive workings and large-scale exploitation and the North Pennines became established as Britain's leading lead and zinc producer (Schellman and Scott, 1970). Lead production peaked in the middle decades of the nineteenth century and zinc production between 1880 and 1920 (Dunham, 1990). The last major metal mine closed in the early 1950s. In the first half of the twentieth century significant production of non-metallic ores (witherite, barytes and fluorspar) took place at several sites in the lower South Tyne valley (Dunham, 1990). Coal mining also has a long history in the Tyne catchment, with peak production dating to the period 1815-1950. Larger-scale operations were largely concentrated in the Lower Tyne valley although there has been significant production in lower parts of both the South and North Tyne valleys.

Current land-use is predominantly agricultural. Thin acidic soils in the upland areas of the catchment generally support moorland vegetation and rough pasture (Jarvis, 1977), and extensive parts of the North Tyne catchment are covered in forestry plantations (Wark and Kielder Forests). Agricultural activity at lower elevations in the North and South Tyne basins is generally limited to sheep on valley hills and hay production in the valley bottoms. The relatively sheltered situation of the main Tyne valley below Hexham allows more intensive farming; arable (barley) cultivation, sheep and cattle for meat and some dairy production. The lowest 25 km of the Tyne valley is heavily industrialised, especially around the major conurbation of Tyneside.

<u>Climate and hydrology</u>

The upland areas to the north and south west of the Tyne basin have a large influence on the prevailing climate. Temperatures tend to be relatively cool compared to the average for England (July maximum of 19.3°C, and February minimum of 0.4°C) and decrease significantly with altitude. Precipitation in the Tyne catchment (Fig. 3.4) shows marked west-east and upland-lowland gradients, with peaks of 1525 mm a^{-1} and 1270 mm a^{-1} in the upper South and North Tyne



<u>Figure 3.4</u> Map of the Tyne Basin showing average annual precipitation and potential evaporation

catchments respectively, falling to 760 mm a^{-1} at the North/South Tyne confluence. The seasonal distribution of precipitation is relatively even with little variation between summer (April - September) and winter totals, though there is a slight tendency for a winter maximum in the west and a summer maximum in the east (Archer, 1981).

Information on longer-term trends in temperature and precipitation is provided by instrumental temperature and precipitation records which are available for a number of locations in north east England. Mean annual temperature variations recorded at Durham Observatory are illustrated in figure 3.5. This shows an overall warming trend until the 1940s, but with a cooler period between 1870 and 1890, and significant cooling since the late 1940s. Long rainfall records are available for several locations within the Tyne catchment. Figure 3.6 shows standardised plots of annual precipitation totals and 5 year mean trends for 4 representative sites; Allenheads (NY 864452) on the River East Allen, a major tributary of the South Tyne, Catcleugh (NT 740030) on the River Rede, Camphill (NY 920764) in the Lower North Tyne catchment and Whittle Dean (NZ 072673) in the Lower Tyne. Although, in detail, there are differences in the rainfall patterns of the North, South and Lower Tyne catchments a number of general trends in the timing and magnitude of major changes are apparent. The 2 longest records, for Whittle Dean and Allenheads, suggest low annual rainfall amounts in the 1850s. All sites record above average precipitation between c.1860 and the mid 1880s, but with high year to year variability. The period between c.1885 and the early 1920s was one of generally low rainfall totals, particularly in lower parts of the catchment (Camphill and Whittle Dean), and with short episodes (around 5 years) of increased precipitation centred on 1898 and 1916 at Allenheads and Catcleugh. High annual totals and low variability were recorded between the mid 1920s and mid 1930s at all sites, but with progressively more pronounced peaks upstream. After the mid

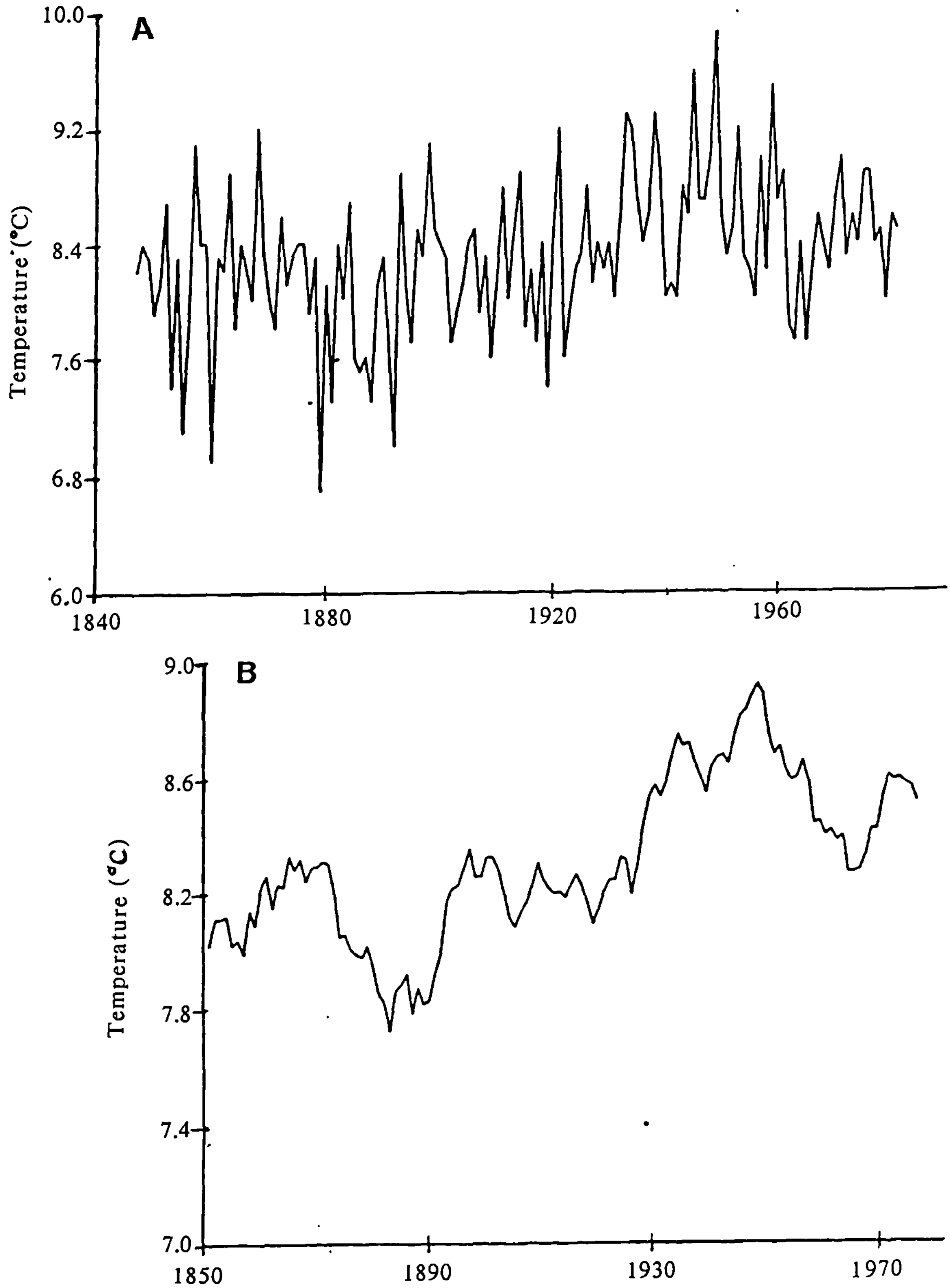
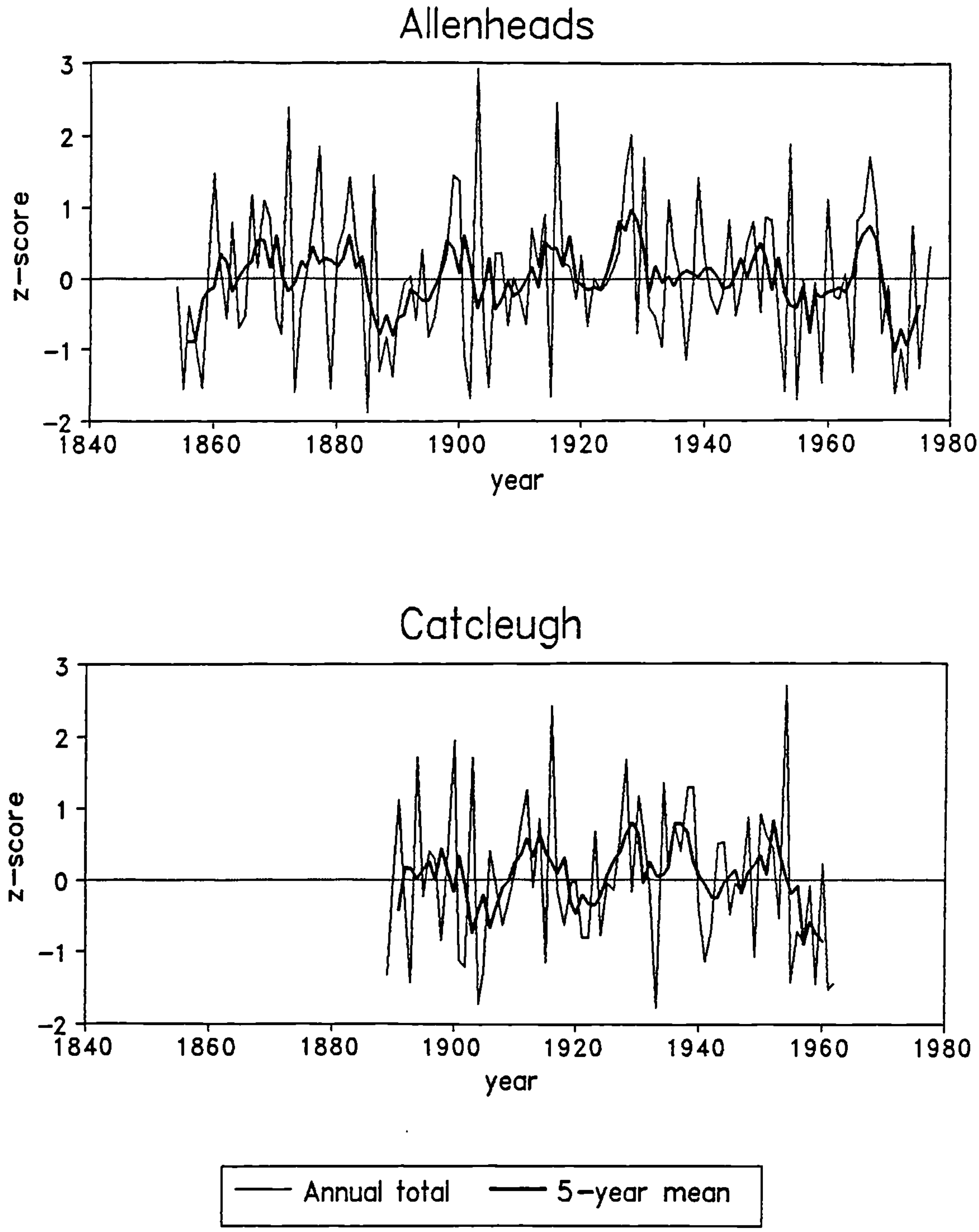


Figure 3.5 (a) Annual mean temperature recorded at Durham Observatory, 1847-1981 (b) Mean temperature series smoothed with a 10-year uniform window filter (from Harris, 1985)



<u>Figure 3.6</u> (a) Standardised plots of annual and 5-year mean rainfall totals for Allenheads and Catcleugh (see Fig. 3.1 for location details)

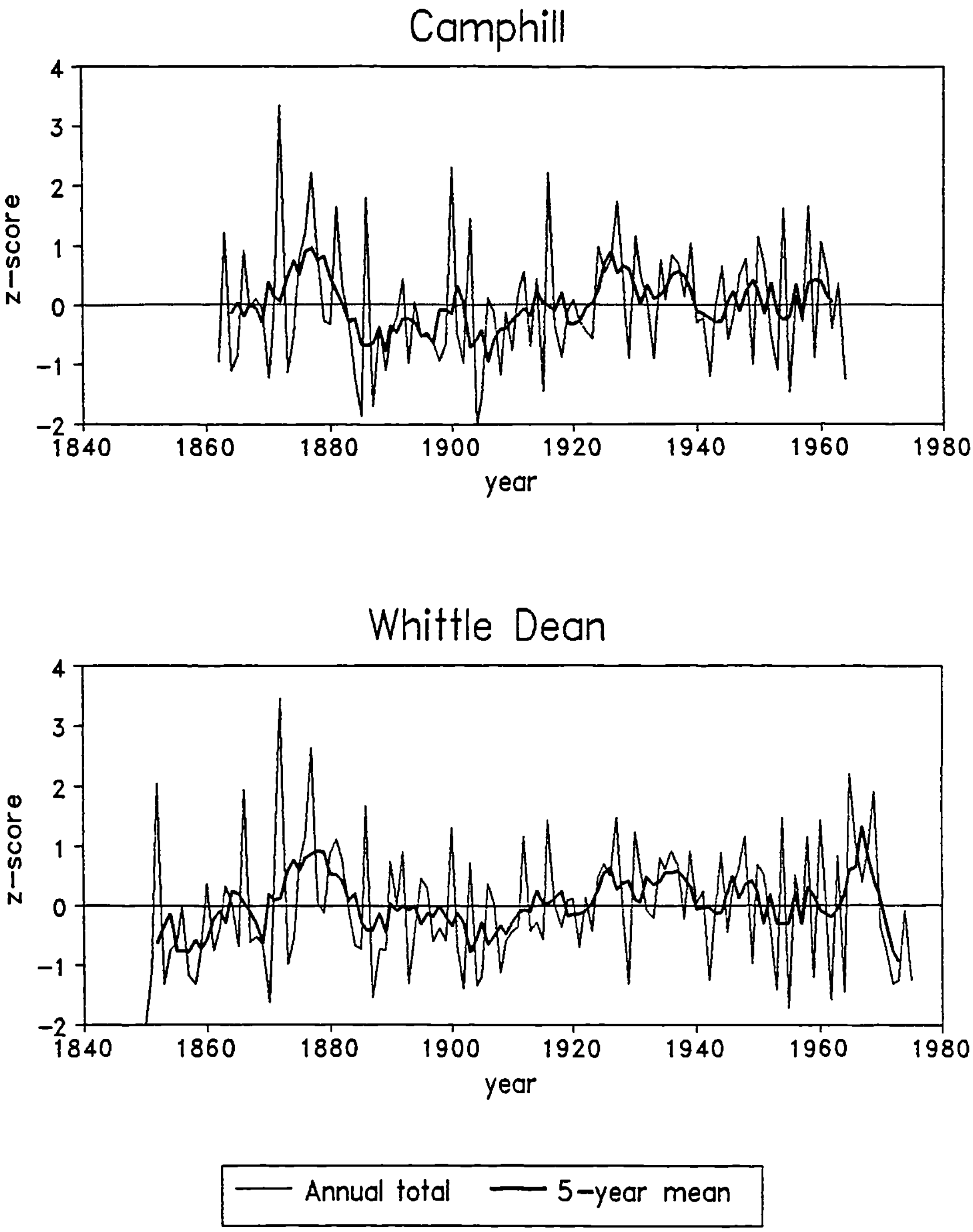


Figure 3.6 (b) Standardised plots of annual and 5-year mean rainfall totals for Camphill and Whittle Dean (see Fig. 3.1 for location details)

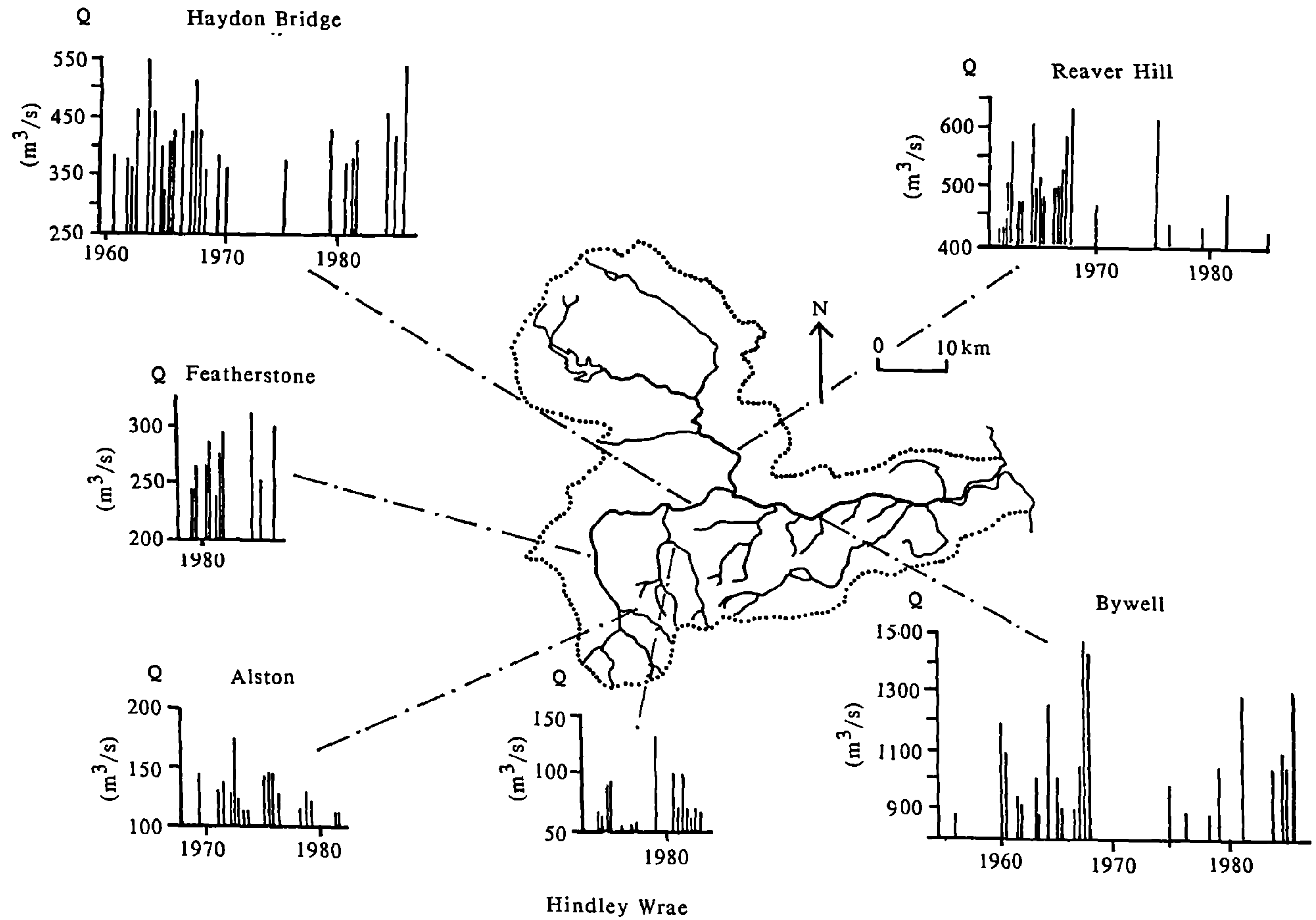
1940s year-to-year rainfall variability seems to have increased. Above average totals were recorded in the late 1940s and mid 1960s at Allenheads, Camphill and Whittle Dean, and all locations show significantly reduced rainfall totals in the 1970s.

The River Tyne is currently gauged at 8 locations. The distribution of gauges is not even, and upland reaches are poorly represented. The first gauging station in the catchment was emplaced in 1939 at Barrasford (NY 920733), on the North Tyne, though most gauges date to the 1960s. The location of gauging stations is shown in Fig. 3.7 along with plots of peak-over-threshold discharges for each site. A combination of steep relief, high precipitation and a high proportion of precipitation appearing as runoff (approx. 64 %, Hall, 1964) produce a rapid response to rainfall and a "flashy" streamflow regime.

A detailed and extended record of flooding prior to instrumentation is available for the Tyne catchment (Appendix I), based on two compilations of documentary evidence (Jones et al, 1984; Archer, unpublished) and additional information from a number of archive sources including newspaper reports, local books and journals (e.g. Brand, 1789; Sykes, 1866; Fordyce, 1877) and meteorological publications. Additionally, floodstones at a number of locations mark the levels of major floods, including those of 1771 and 1815 (the two largest on record). This information extends the flood data base considerably, and provides a relatively comprehensive record of major floods since 1699 (Fig. 3.8). Comparison of the documentary flood record plotted in figure 3.8 with the long-term precipitation plots (Fig. 3.7) shows a clear relationship between periods of above average annual precipitation and increased frequency of flooding in the Tyne catchment.

Previous fluvial geomorphological studies in the Tyne catchment

Previous and ongoing studies in the catchment provide background information on channel, floodplain and valley development over a range of timescales.



<u>Figure 3.7</u> Plots of peak-over-threshold flows for selected gauges in the Tyne catchment

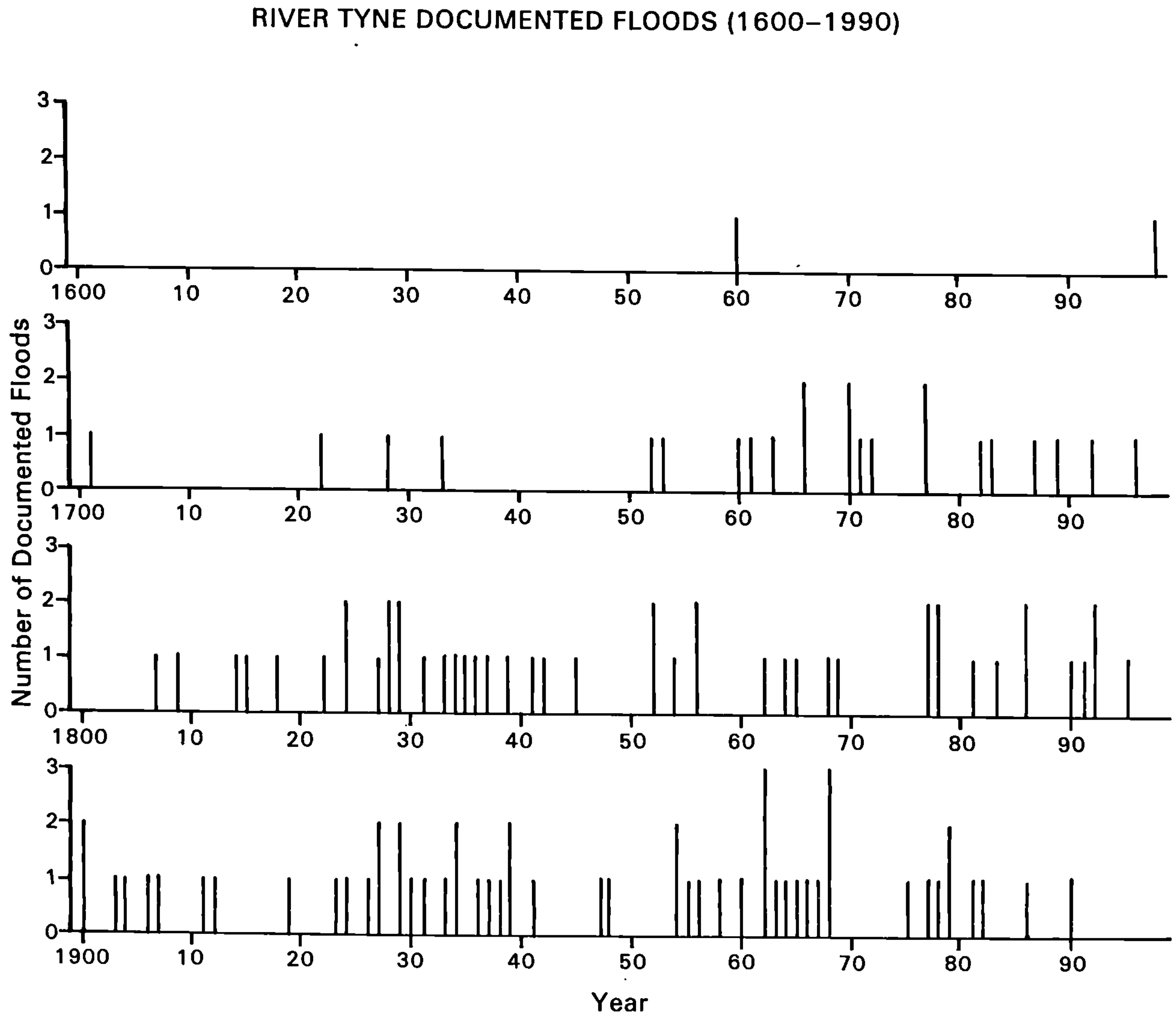


Figure 3.8 Documented floods in the Tyne Basin since 1600 A.D.

i) Short-term (<10 years) studies have investigated transport and deposition of coarse and fine sediment. A Ph.D study by Glover (1975) examined variations in the hydrochemistry of suspended sediment transport in the South Tyne over individual flood hydrographs. More recently Macklin has looked at chemical and physical speciation (Macklin and Dowsett, 1989) and downstream geochemical variations (Macklin, 1988) in contemporary fine-grained overbank flood sediments. Nature and rates of gravel and cobble bedload transport have been examined in several Ph.D studies, concentrating on coarse sediment hydraulics and spatial patterns of sediment movement on reaches of the North and South Tyne (Hall, 1964), estimation and measurement of bedload discharge at Bywell in the Lower Tyne (Muir, 1968) and transport in riffle-pool sequences on regulated reaches of the North Tyne (Sear, ongoing).

ii) Investigations of fluvial development over medium timescales ($10\text{-}10^2$ years), largely within the South Tyne catchment, have focussed on the impact of upstream heavy metal mining at channel and floodplain locations (e.g. Macklin, 1986) and downstream sediment transfer (Macklin and Lewin, 1989).

iii) Over longer-timescales ($10^2\text{-}10^3$ years) ongoing work is concerned with the reconstruction and interpretation of the Holocene alluvial sequences in the Tyne catchment, looking at controls and causal mechanisms governing alluvial sedimentation and erosion (e.g. Macklin and Passmore, 1988; Macklin, Passmore and Rumsby, in press; Passmore et al, in press).

This study fits well into this overall framework, providing detailed information on flood regime and channel and floodplain adjustment over the last several hundred years allowing an opportunity to establish linkages between longer-term work and process studies for reaches outside of areas directly affected by metal mining.

Chapter 4

HISTORIC FLOOD SEDIMENTATION AT LOW PRUDHOE IN THE LOWER TYNE VALLEY

Introduction

This chapter considers the reconstruction of a palaeoflood record for the Lower Tyne valley using fine-grained vertically accreted floodplain sediments deposited at Low Prudhoe (NZ 088637) (Fig. 4.1), 15 km west of Newcastle upon Tyne. The River Tyne at Low Prudhoe has a relatively low gradient (0.001 m m^{-1}) and drains an area of 2198 km^2. In terms of floodplain morphology and patterns of sedimentation Low Prudhoe is fairly representative of the Lower Tyne. Two important factors facilitated the choice of study site. Firstly, recent bank erosion has provided unusually good exposure of alluvium; extensive floodplain sections comprising 2-3 m of finely laminated sands and silty sands overlying 2 m of sandy gravels. Preliminary granulometric analysis of prominent coarse sand layers in the upper fine-grained unit showed them to have similar properties to sands deposited on the Tyne floodplain during a major flood in August 1986 (Macklin and Dowsett, 1989), suggesting that sediments at this site could provide a valuable palaeoflood record for the Lower Tyne Valley. Secondly, the documented and monumented flood record is especially detailed in the Low Prudhoe area. A number of local commentators recorded details of floods in the vicinity (e.g. a succession of headmasters at Ovingham School, NZ 083638) recorded flood details in the school log book), and floodstones at Ovingham Rectory (Fig. 4.2) mark the levels of the great floods of 1771 and 1815 (the two largest on record). Together these make Low Prudhoe an excellent site at which to compare documentary and sedimentary flood histories and to assess the utility of the latter.

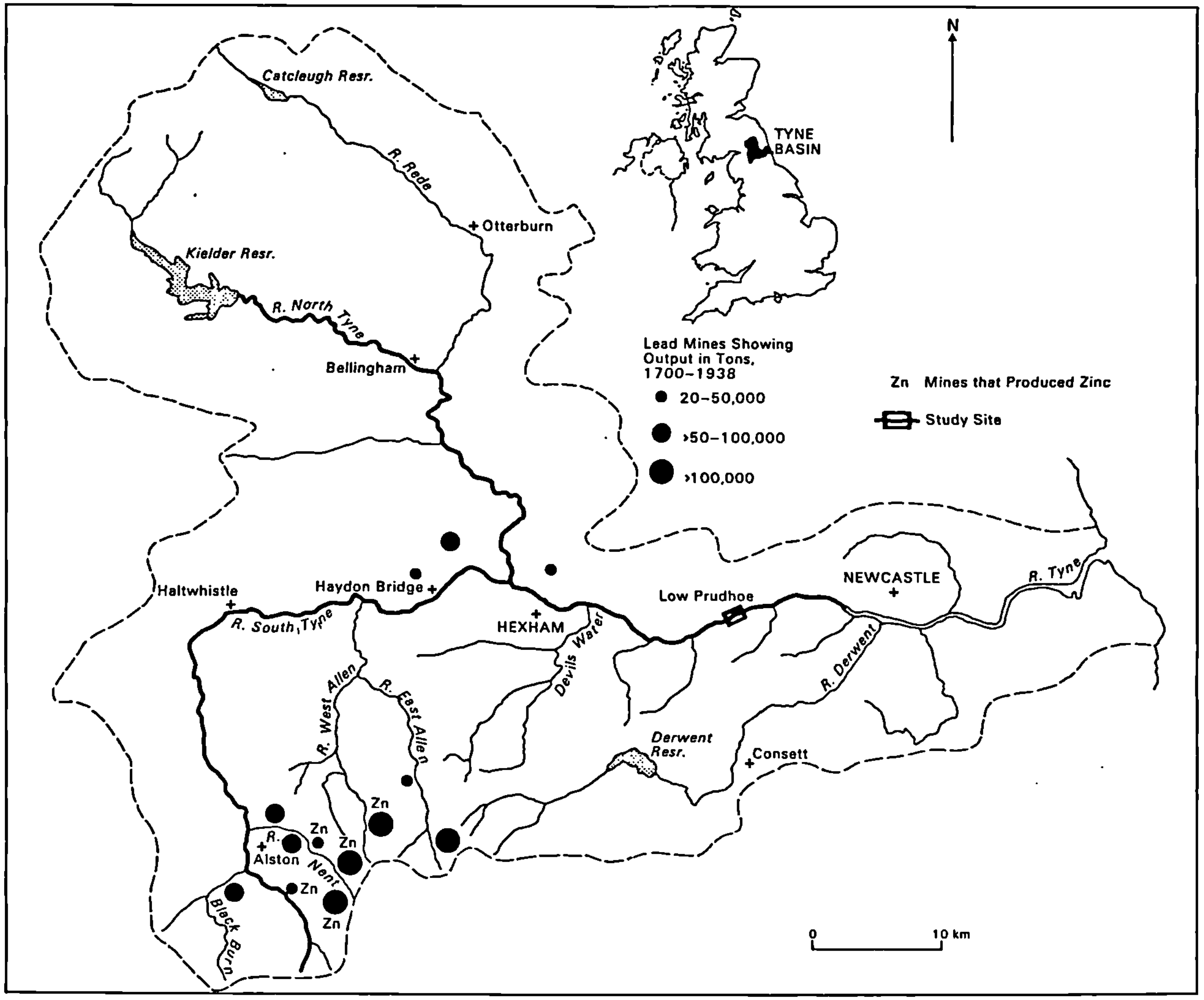


Figure 4.1 Map of the Tyne Basin showing location of the study reach at Low Prudhoe, drainage network and metal mines

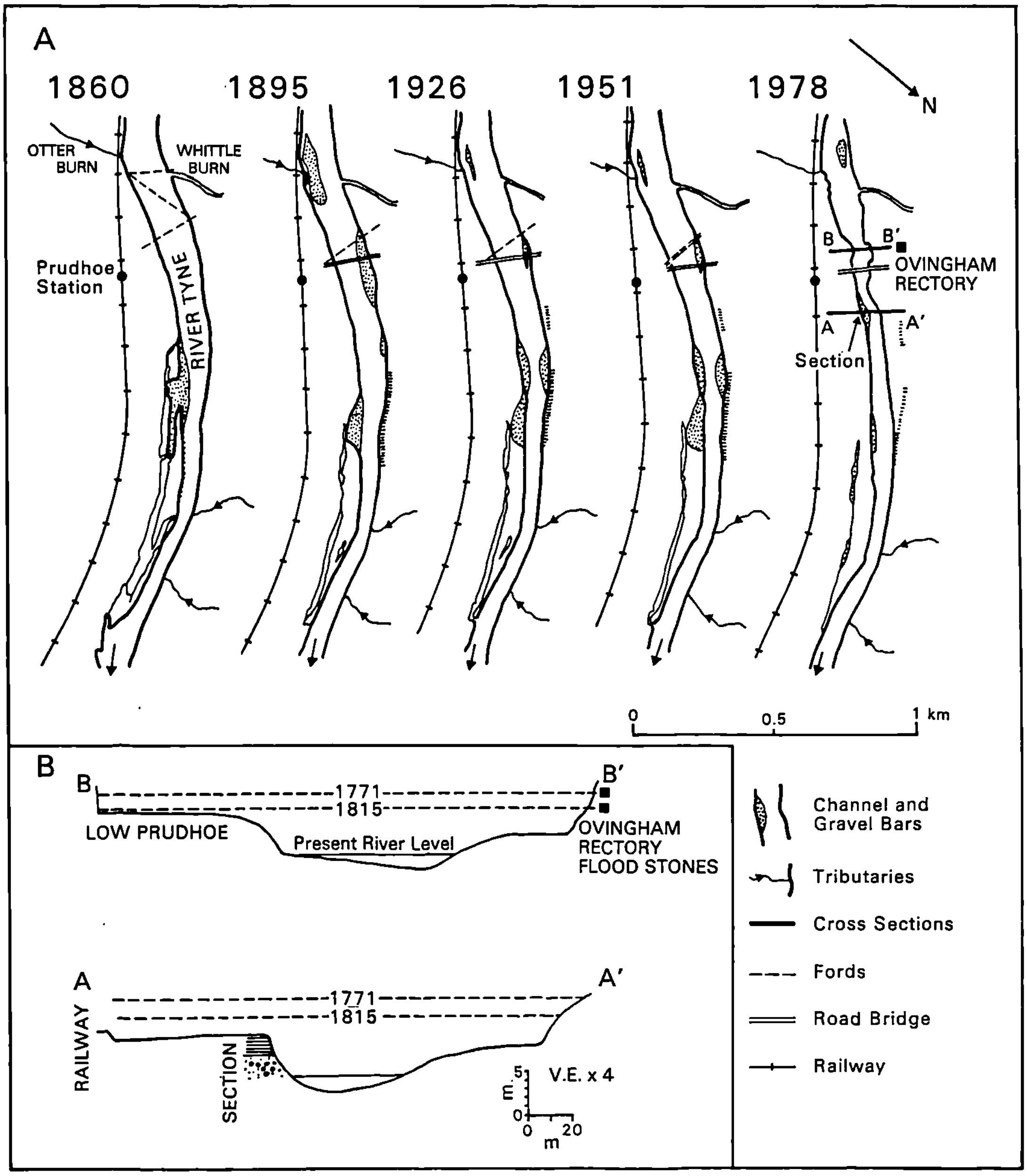


Figure 4.2 (a) Maps showing channel change at Low Prudhoe between 1860 and 1978, and location of section (b) Channel cross-sections upstream and downstream of Ovingham Bridge. Relative heights of 1771 and 1815 floods are indicated

River channel change and vertical accretion processes

Over the last 130 years or so, the thalweg of the Tyne at Low Prudhoe has moved very little (Fig. 4.2a), but since the early 1950s its channel has narrowed appreciably - most notably in a 500 m reach downstream of Ovingham Bridge, within which the study section is located. Channel narrowing has been primarily the result of incision which elevated former lateral gravel bars above the level of the low flow channel and enabled them to be colonised by vegetation. These sites subsequently became the focus of fine sediment deposition resulting in the infilling of side channels and attachment of the bars to the former river bank. Rates of incision and bed erosion increased considerably in the late 1950s and 1960s following gravel extraction from the River bed (Muir, 1968), and is still continuing today necessitating regular upgrading of the footings of Ovingham Bridge.

The sands and silty sands exposed in the river bank at Low Prudhoe display heterolithic stratification (cf. Thomas et al, 1987) and are believed to have been formed by vertical accretion. This deposit has a similar surface morphology (asymmetric in cross section with its highest point located adjacent to the channel, see Fig. 2b) and stratigraphy (see below) to shrub and herb covered alluvial benches located within the present Tyne channel which accrete fine sediment to the level of the contemporary floodplain. These are not levees or overbank splays but resemble alluvial benches described by Page and Nanson (1982) and Taylor and Woodyer (1978) in several Australian and Canadian rivers and defined as "actively accreting flat-topped bodies of sediment occurring along the banks of a stream channel" (Woodyer et al, 1979). Initial sedimentation at the study section was therefore under sub-bankfull conditions with fine-sediment deposition confined within the channel banks. Later sediments, as the result of progressive vertical accretion, would have tended to be deposited under flow conditions closer to bankfull and also by overbank floods. Thus a considerable portion of fine-grained alluvium at Low Prudhoe is believed to represent the vertical component of within-channel sedimentation and is of a somewhat different origin to "overbank" fines (usually of silt and clay size and deposited at some distance from the channel) more frequently described on British floodplains (e.g. Lambert and Walling, 1987).

<u>Field sampling and laboratory analysis of flood sediments</u>

Fine-grained alluvial sediments in the upper part of the river bank section at Low Prudhoe were sampled using Kubiena tins in order to obtain a complete vertical section. In the laboratory the 2.41 m long monolith was cleaned and drawn, and sub-samples (135 in total) taken from every distinct layer for metal analyses and organic matter determinations. Additional material for grain-size analysis was collected from the coarser, more prominent sand units (13 samples). Sediment colour was described using Munsell notation.

All samples were air dried, passed through a 2 mm sieve and total heavy metal contents were estimated from the amounts of metals brought into solution by digesting in nitric acid following standard procedure (e.g. Horowitz, 1985). Metal (lead, silver and zinc) concentrations were determined (Appendix II) using atomic absorption spectrophotometry (Philips SP2900 with computer) involving direct aspiration of the aqueous solution into an air-acetylene flame. The organic content of sediments was taken as the loss of weight on ignition (L.O.I.) at 450°C (Broadbent, 1965). Mean grain size, sorting, skewness and kurtosis were determined graphically following Folk and Ward (1957).

<u>Sedimentary sequence and grain-size characteristics of flood sediments</u>

Flood events in fine-grained alluvial deposits at Low Prudhoe are represents by layers of generally flat-bedded sands and silty sands (Fig. 4.3), which on the basis of grain-size (following Niggli, 1983 and Pettijohn, 1975) and colour can be assigned to one of three sedimentary categories (detailed below). Summary grain-size curves for these flood sediment types are shown in Fig. 4.4.

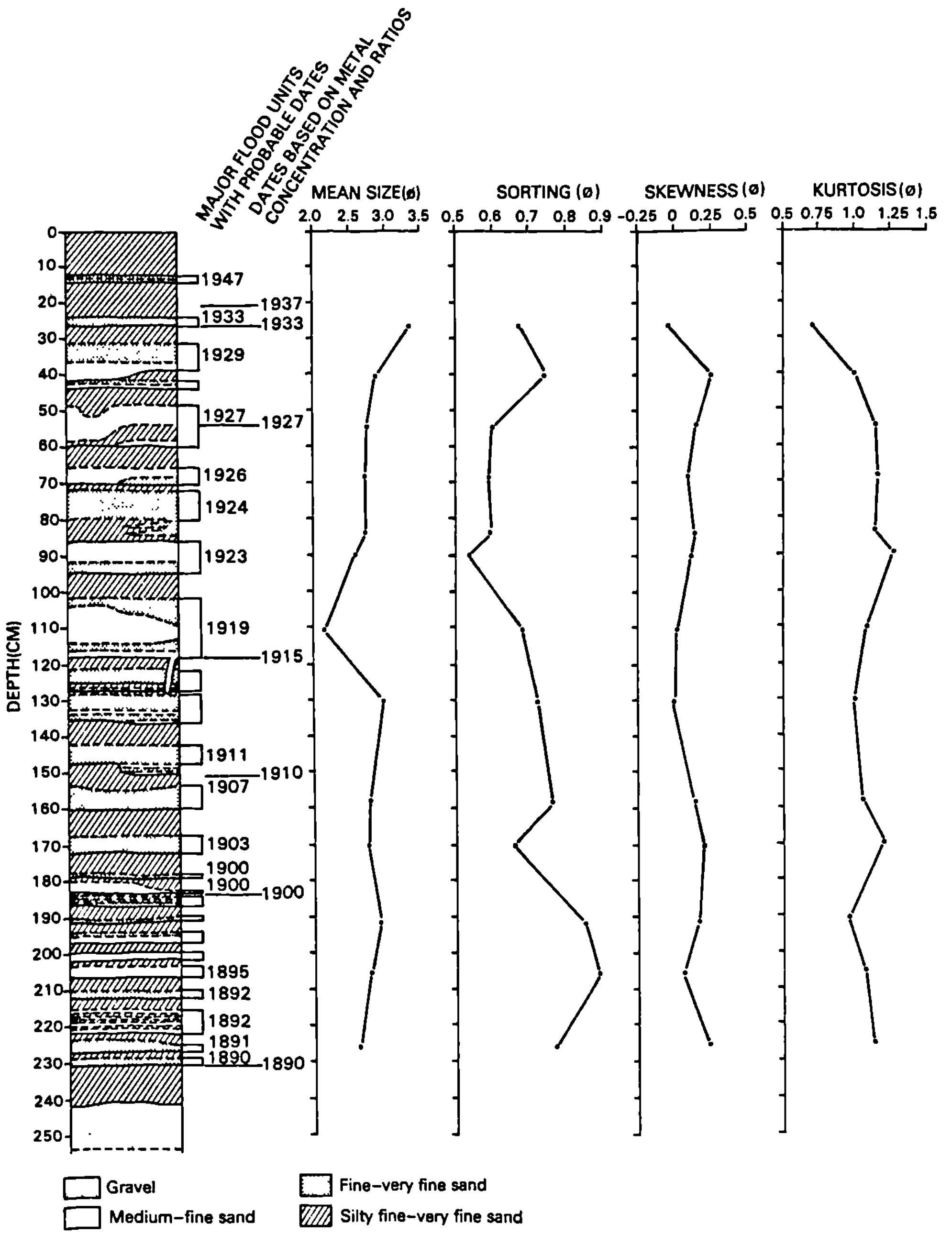


Figure 4.3 Sedimentary log and summary moment statistics of vertically accreted alluvium at Low Prudhoe

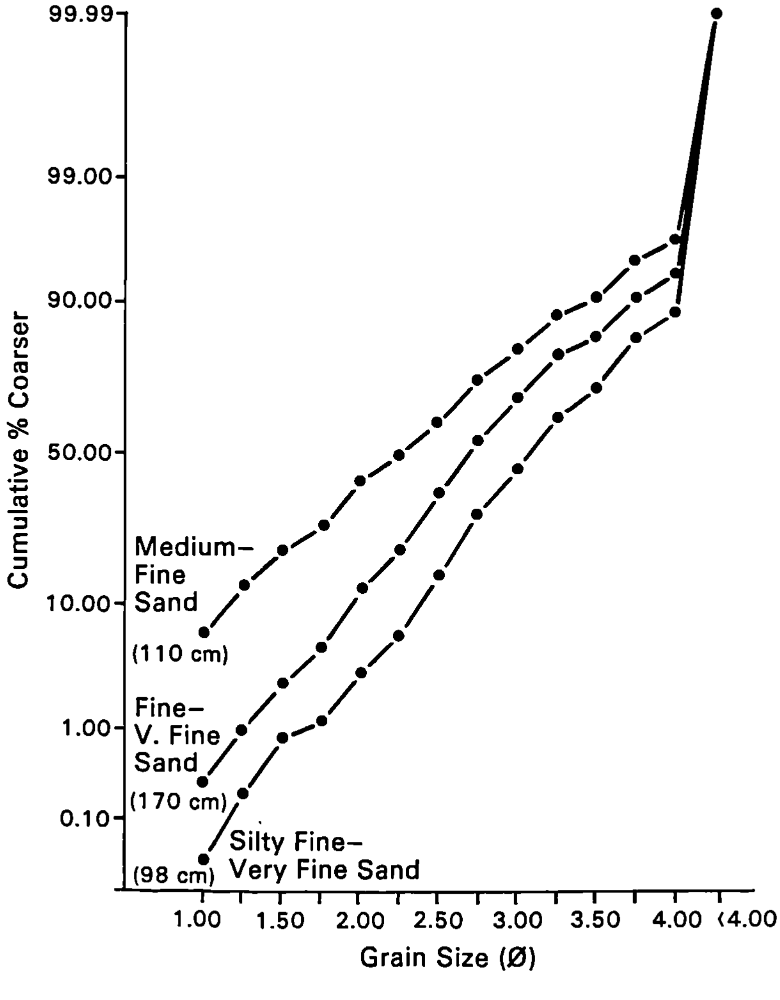


Figure 4.4 Grain size curves for type 1 (medium-fine sand), type 2 (fine-very fine sand) and type 3 (silty fine-very fine sand) flood units

Type 1 flood unit: medium-fine sand

Yellow brown in colour (10 YR 5/4), mean grain-size between 2.1 and 2.7 Ø, mean L.O.I. 2.4 % and with generally less than 5 % silt and clay.

Type 2 flood unit: fine-very fine sand

Dark yellowish brown in colour (10 YR 3/4), mean grain-size between 2.7 and 3.3 Ø, mean L.O.I. 3.3 % and with 5-10 % silt and clay.

Type 3 flood unit: silty fine-very fine sand

Dark brown in colour (7.5 YR 3/4), mean grain size 3.3 Ø, mean L.O.I. 3.7 % and with more than 10 % silt and clay.

Following Knox (1987), textural discontinuities formed by layers of medium-fine (type 1 flood unit) and fine-very fine (type 2 flood unit) sand that reverse the overall fining upward sequence are interpreted as the deposits of large floods. Finer-grained silty sands (type 3 flood unit) are believed to represent lower magnitude floods or sediment deposited on the falling stage of a large flood event. Where coarser type 1 or 2 flood deposits overlie finer-grained type 3 flood units boundaries are generally sharp and sometimes marked by angular unconformities (e.g. 80 and 40 cm), probably produced by scour at the initial stages of a flood (cf. Jahns, 1947). In contrast, where type 3 flood unit overlies type 1 or 2 flood deposits (e.g. 102 and 168 cm) bounding surfaces are more usually gradational, fining upwards over 1-2 cm. In such cases finer sediment is believed to have been deposited on the falling limb of a flood hydrograph producing a flood "couplet" similar to flood units identified by Mansfield (1938), Farrell (1987), Klimek (1974) and Knox (1987). Alternatively, sharp, non-gradational transitions from type 1 or 2 to type 3 flood units are the product of one or, more probably, several lower magnitude events. Higher percentages of organic material towards the top of many type 3 units suggest incipient soil development and slower accumulation rates.

Complex grading is evident within several of the sedimentation units believed to have been deposited by larger floods (e.g. 222-215, 187-185, 118-102, 60-48, 42-32 cm). This is likely to have resulted from changing flow conditions during a multi-peaked hydrograph (Taylor and Woodyer, 1978), varying sources of sediment or periodic upstream bank collapse during a flood event (Osterkamp and Costa, 1987). Mudcracks (e.g. 118 cm), scour hollows (e.g. 183-180, 42-40 cm) and other pre-existing surface irregularities are also useful for differentiating between flood units. On the basis of these and the other sedimentological criteria defined above, 25 large flood units would appear to be represented in the alluvial profile at Low Prudhoe.

Vertical variations in the mean size and summary moment statistics of the thickest and best developed major flood units are plotted in Fig. 4.3. In general, flood units become finer, relatively better sorted and more platykurtic upsection. Moment statistics also pick out major textural discontinuities, corresponding with significant changes in flood unit thickness, at 184, 118 and 32 cm. In the lower unit (230-184 cm) grain size decreases upsection with flood units becoming more poorly sorted and platykurtic. Between 184 and 118 cm this trend continues although flood units are generally more leptokurtic. In the upper sequence (118-32 cm) coarser, well-sorted, leptokurtic flood sediments at the base are followed by progressively finer, less well-sorted and platykurtic flood deposits. Although graphical moment statistics confirm the basic facies architecture and stratigraphy of the Low Prudhoe section, they are less useful for identifying the upper and lower boundaries of flood units which can only be delineated by very careful logging of the profile. Establishing precisely the number, thickness and sedimentary characteristics of major flood units is of paramount importance for reconstructing the history of flooding at a site.

Trace metal dating of flood sediments

A maximum age for initiation of fine-grained vertical accretion at Low Prudhoe is provided by a ^{14}C date of 500 +/- 50 cal years BP (Beta-37797) from an *in-situ* tree stump located to the top of the underlying gravels. More detailed age estimates for flood events have been obtained by relating vertical changes in sediment trace metal concentration at Low Prudhoe to metal ore production in the Tyne Basin (Figs. 4.5 and 4.6). In common with other river systems in Britain draining metal mining area (Lewin and Macklin, 1987), effluent from the extraction and processing of lead and zinc ores resulted in the release of large quantities of fine-grained, metal-rich waste into the River Tyne. Sediment-borne heavy metals transported alongside "normal" alluvial sediment, provide a distinctive source of "labelled" sediment. Furthermore, as the development and history of metal mining in the Tyne Basin is known in some detail (Dunham, 1990; Raistrick and Jennings, 1965; Smith, 1923), these heavy metals can be used as stratigraphic markers to indicate the age of flood deposits. Water used in ore-processing, heavily laden with metal-rich sediment, was usually discharged directly into the nearest stream. The fine-grained mining waste was then transported along with the "normal" suspended load of the river. Given that gravel- bed rivers generally provide limited transient storage of suspended sediment (Desloges and Church, 1981; Lambert and Walling, 1988) the time interval between the release of metals from upstream mining operations and their incorporation in vertically accreted alluvium downstream is likely to have been minimal (probably ranging from a few weeks to less than a year). In the lower Tyne valley, although mining waste was important in terms of sediment metal concentrations, major lead and zinc mines lay some distance upstream, and sediment released from mining constituted only a relatively small proportion of vertically accreted alluvium.

As has been shown in mining age alluvium elsewhere in the Tyne basin (Macklin, 1986; Macklin and Lewin, 1989; Macklin and Smith, 1990) especially high zinc levels and lead/zinc ratios mark the peak of zinc extraction in the

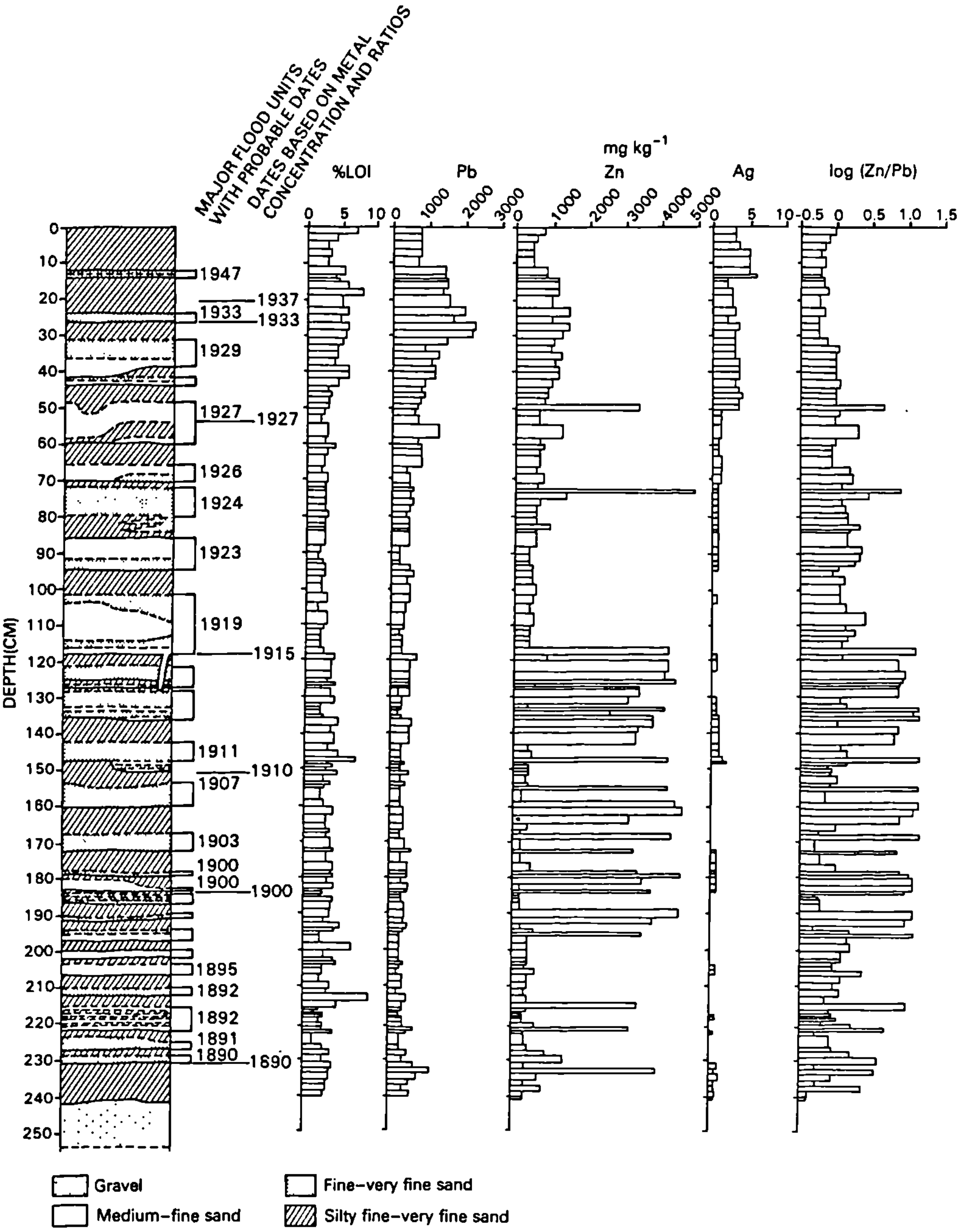


Figure 4.5 Metal concentrations and organic matter content in vertically accreted alluvium at Low Prudhoe showing major flood units with their probable dates

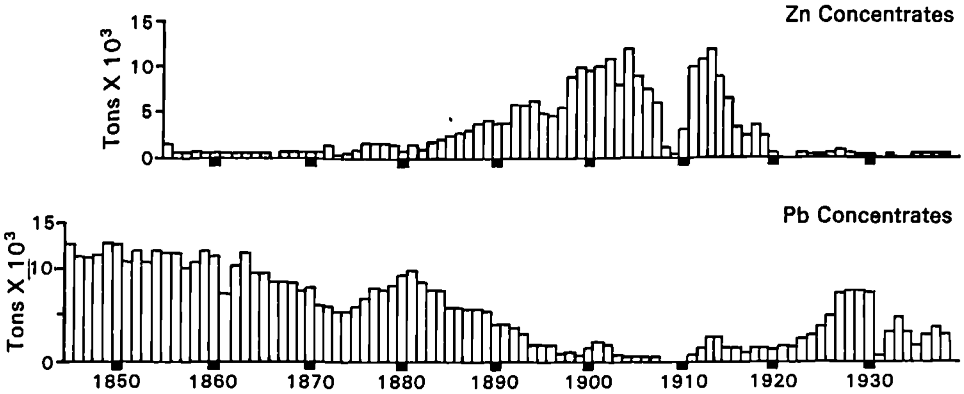


Figure 4.6 Lead and zinc production in the Tyne Basin 1845-1938 (after Dunham, 1944)

Allendale and Alston Moor orefields between 1897 and 1915 (Fig. 4.6). At Low Prudhoe this is evident in sediments between 196-118 cm. Above 118 cm zinc concentrations decline corresponding with the demise of zinc mining in the region after 1915 (Dunham, 1944). Comparatively low lead levels (<1000 mg kg^{-1}) below 90 cm indicate sedimentation at Low Prudhoe post-dates the main phase of lead production in the Tyne basin that ended in 1880, confirming age estimates provided by sediment zinc concentrations. Above 90 cm lead concentrations rise in response to the revival of lead mining in the 1920s and 1930s. Peaks in lead production in 1927, 1933 and 1937 are reflected by increased lead concentration in sediments and decreased zinc/lead ratios at 56, 28 and 24 cm. Most lead veins in the Tyne basin are argentiferous (Dunham, 1948) and changes in silver concentrations generally follow those of lead. To summarise, trace metal dating of fine-grained palaeoflood sediments at Low Prudhoe indicate that the major part of the sequence was deposited over a comparatively short period of time (c.50 years) between 1890 and 1937.

Flood frequencies at Low Prudhoe 1890-1990: a comparison of the documentary and sedimentary flood record in the Lower Tyne valley

On the basis of dating control provided by sediment heavy metal analyses, and in the knowledge that archive sources tend to record larger spatially extensive floods (Archer, 1987) flood units evident in the Low Prudhoe section were assigned as far as possible to documented floods since 1890 in the lower Tyne Valley (Table 4.1, Fig. 4.7). Not all flood units, however, could be related to recorded flood events and in these cases chemostratigraphic dating control provided general bounded time limits. In Fig. 4.7 floods documented in the Lower Tyne between 1890 and 1989 are plotted with the sedimentary flood record (where present) over the same period and compared below on a decade by decade basis.

Year	Day	Month	Year	Day	Month	Year	Day	Month
1891	24	AUG.	1930	26	JULY	1960	10	OCT.
1892	02	SEPT.	1931	07	NOV.	1962	03	FEB.
1892	03	NOV.	1933	01	FEB.	1962	27	AUG.
1895	03	AUG.	1934	07	MARCH	1962	11	SEPT.
1900	06	OCT.	1934	14	APRIL	1963	21	NOV.
1900	27	OCT.	1936	14	DEC.	1964	08	DEC.
1903	09	OCT.	1938	08	OCT.	1965	30	JULY
1904	24	NOV.	1939	09	JAN.	1967	17	OCT.
1906	30	MAY	1939	01	DEC.	1968	23	MARCH
1907	09	JUNE	1941	17	FEB.	1968	13	SEPT.
1911	14	MAY	1947	22	APRIL	1975	30	AUG.
1912		JUNE	1948	20	AUG.	1976	21	JAN.
1919	01	NOV.	1953	12	NOV.	1977	26	JAN.
1923	13	NOV.	1954	03	APRIL	1978	28	DEC.
1924	30	DEC.	1954	18	OCT.	1979	29	MARCH
1926	20	SEPT.	1954	02	DEC.	1979	26	NOV.
1927	23	JULY	1955	10	JAN.	1981	03	MARCH
1927	21	SEPT.	1956	17	FEB.	1986	26	AUG.
1929	10	AUG.	1956	28	AUG.	1990	04	FEB.
1929	16	NOV.	1958	12	FEB.	1991	24	FEB.

Table 4.1 Documented floods in the Lower Tyne 1891-1990 as recorded in local newspapers, books, journals and meteorological publications

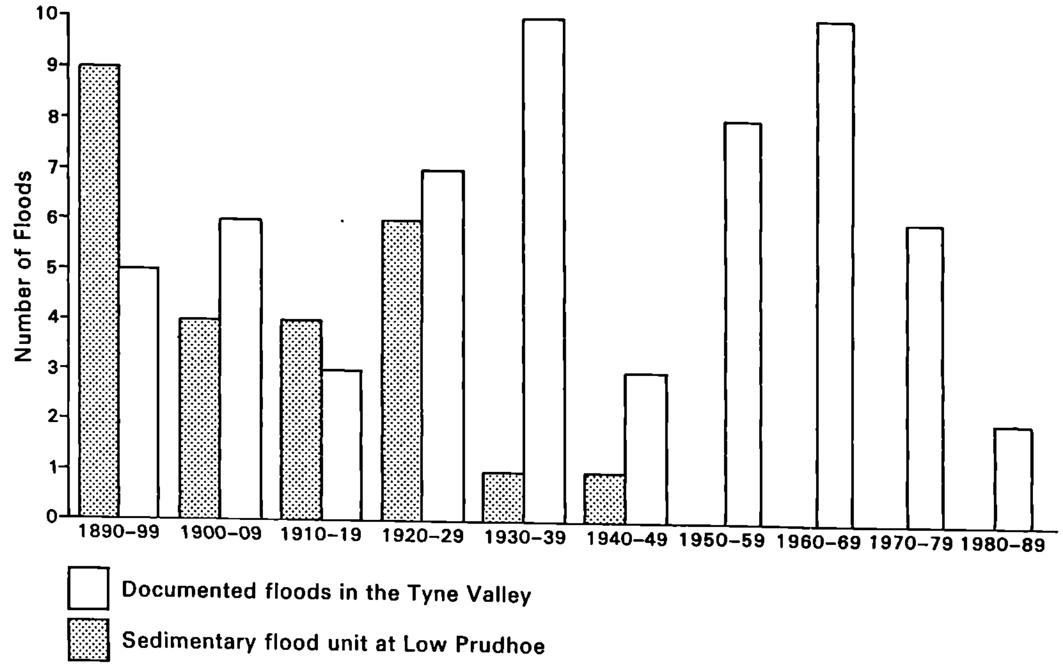


Figure 4.7 Comparison of floods documented in the lower Tyne Valley (between 1890 and 1989) and the sedimentary flood record at Low Prudhoe

1890-1899

The sedimentary sequence for this period contains many more flood events than are documented in archive sources (Fig. 4.7 and Table 4.1). This can be explained by a small height difference between the depositional surface and river bed at this time resulting in more frequent inundation by sub-bankfull flows. Although the accretionary surface at Low Prudhoe was probably flooded several times a year (as indicated by the large number of floods dated to the 1890s), individual flood units are relatively thin (2-3 cm) and suggest deposition by relatively low magnitude events. Indeed, very few of these floods were sufficiently large to merit being recorded by contemporary commentators. Thicker, coarser layers, however, probably correspond to higher magnitude floods (e.g. those of 1891 and 1892).

1900-1909

Sedimentary and documentary based flood records are more closely matched than in the previous decade. After 1900 (c.180 cm) the thickness of individual flood units increases significantly (>10 cm). Zinc concentrations also increase, reflecting the input of large quantities of metal-rich fines into the South Tyne system during the peak of zinc mining, 1898-1915. Lower zinc levels between 160-142 cm probably mark the temporary fall in zinc production between 1906 and 1910, though this coincides with, and may well have been accentuated by, the North Tyne floods of 1907 and 1911 that would have introduced fine sediment with low metal concentrations into the River Tyne.

1920-1929

Six large flood events are evident in the part of the Low Prudhoe profile dated to the 1920s (c.100-30 cm), one less than recorded in archive sources. Flood units are generally coarser (medium-fine sand) and thicker than those of earlier decades, reflecting a large input of fine sediment generated by bank erosion (noted by commentators, e.g. Northumberland River Board, 1950) during a series of very large floods in 1923, 1924 and 1926. Low sediment metal concentrations are the consequence of a marked reduction in the supply of mining-related fine material, following the closure of many mines at the end of World War I. Flood units with higher zinc concentrations and zinc/lead ratios (e.g. 60-50 cm) were probably derived from reworking of earlier metal contaminated alluvium located some distance upstream.

1930-1949

Although the documentary record for this period shows the frequency of large floods remained high (particularly during the early to mid 1930s) only two distinct flood units, dated to 1933 and 1947, can be recognised. Thus by the early 1930s the alluvial surface at Low Prudhoe appears to have accreted to a level above the channel thalweg that could only be overtopped by floods of a much higher magnitude and reduced frequency than before.

Post 1949

Since 1947 only two exceptional floods have inundated the Low Prudhoe section, those of January 1955 (the largest flood in the Tyne since 1771) and August 1986 (the largest flood since 1955). River bed incision (up to 2 m, Fig. 4.2b), which probably began sometime in the 1940s, transformed the alluvial bench at Low Prudhoe (a site of rapid vertical accretion between 1890 and 1937) into a low terrace. Many reaches of the Rivers South Tyne and Tyne, similar to the Tyne at Low Prudhoe, have incised since World War II (Macklin and Lewin, 1989; Muir, 1968) in response to gravel extraction from channels (gravel was dug from the bed of the Tyne immediately upstream of Ovingham Bridge in the 1950s and 1960s) and bed erosion following the 1947 and 1955 floods. Widespread channel degradation also occurred during the August 1986 flood (Newson and Macklin, 1990), although a thin (2-3 mm) and patchy veneer of fine sand was deposited overbank at Low

Prudhoe during this event. Five years on bioturbation processes have mixed this deposit with earlier sediment, to the extent that it is now very difficult to recognise as a distinct flood unit both in its original thickness and distribution.

Summary

The documentary flood record of the Lower Tyne between 1890 and 1949 shows an increase in flood frequency between 1890-1909 and 1920-1939 with relatively few floods in the decades 1910-1919 and 1940-1949. Flooding over this period (1890-1949) follows changing hydrometerological conditions in north east England, with increases in flood frequency corresponding with rainfall maxima recorded in the region during the late nineteenth century and again between 1920-1939 (Table 4.1).

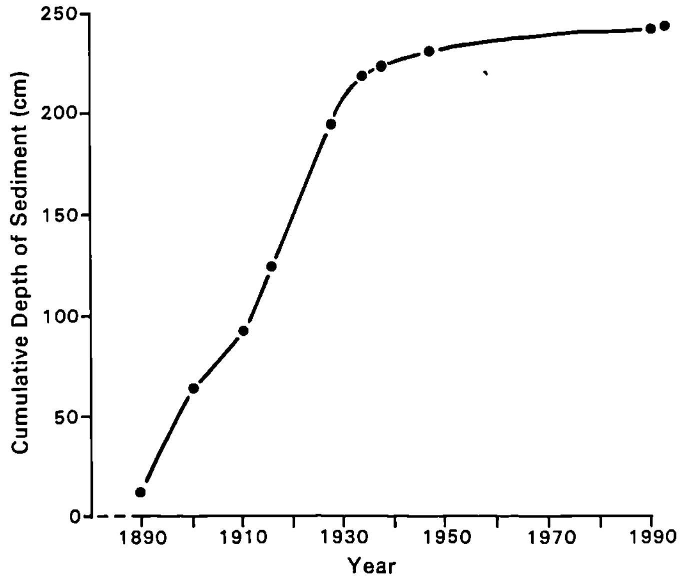
Most of the flood units deposited before 1900 appear to have resulted from sub-bankfull flows many of which will not have been reported by local commentators or newspapers. The similar number of floods between 1900 and 1929 evident in both the stratigraphic and documentary flood record, however, suggests type 1 and 2 flood units were deposited during overbank events that inundated both the alluvial bench at Low Prudhoe and the Tyne Valley floor. Since 1930 an increase in the relative height of this surface above the river bed (resulting initially from sediment accretion and later by channel incision) has effected a "censoring" of the alluvial palaeoflood record to reflect progressively less frequent and larger floods. Today continuing river bed incision has enlarged the Tyne channel at Low Prudhoe to a size that can accommodate floodwaters and sediment in all but the very largest floods.

The disparity between the alluvial stratigraphic and documentary flood records at Low Prudhoe over the last 100 years is believed to reflect the latters bias towards recording large overbank floods. Archive sources will therefore inevitably under-represent the actual number of flood events recorded in the stratigraphic record when a depositional surface is of low elevation and subject to inundation by low magnitude floods. Deposition of fine-grained flood sediment within the Tyne channel (which at Low Prudhoe forms the basis of the palaeoflood record) though reflecting in a systematic way changes in flood flow magnitude and frequency (controlled primarily by climate) has also been strongly influenced by variations in sediment supply (associated with upstream bank erosion rates) and entrenchment of the channel over the period of investigation. It is therefore imperative that sediment availability and the vertical tendency of a channel reach are evaluated, and quantified, before stratigraphic evidence at a site is used to extend the flood series in a river basin.

Vertical accretion rates at Low Prudhoe 1890-1990

Rates of vertical accretion at Low Prudhoe from the end of the nineteenth century up to the present have been calculated by comparing the thickness of flood sediment accumulated between dated flood horizons (Fig. 4.8). There is a fairly close inverse relationship between organic matter in vertically accreted sediments and sedimentation rates (Table 4.2), similar to that found by Knox (1987b) in Upper Mississippi floodplain sequences in the U.S.A.. Alluvial surfaces that are characterised by low rates of sedimentation tend to accumulate organic material in an incipient soil A horizon, whereas surfaces experiencing rapid alluviation normally accumulate relatively small amounts of organic matter (cf. Knox, 1987b).

Between 1890 and 1937 vertical accretion rates at Low Prudhoe were high, averaging 4.8 cm a^{-1}. Since the 1930s, however, average yearly sedimentation rates have decreased by an order of magnitude to less than 0.4 cm a^{-1} at the present day (Fig. 4.8). Nevertheless, rates of recent fine-grained vertical accretion in the lower Tyne Valley are unusually high for British rivers (Table 4.3) and match rates recorded in some of the major river systems of Australia, Europe and North America reviewed by Bridge and Leeder (1979). The large sand load of the Tyne, derived from the breakdown and erosion of Carboniferous sandstone lithologies that underlie most of its catchment, appears to



<u>Figure 4.8</u> Sediment accumulation curve for Low Prudhoe 1890-1989

Depth (cm)	Date	Sedimentation Rate (cm a^{-1})	Mean LOI (%)
0	1990		
		0.3	4.2
10	1950		
		0.8	5.5
18	1940		
		1.2	5.3
30	1930		
		7.0	2.9
100	1920		
		5.0	3.1
150	1910		
		3.0	3.3
180	1900		
		5.0	3.1
230	1890		

Table 4.2 Rates of fine-grained vertical accretion at Low Prudhoe 1890-1990

Author	River Basin	Catchment Area (km^2)	Sedimentation Rate ($cm\ a^{-1}$)	Time Scale (yr BP)
Brown 1987	Severn	10000	0.14	0-10000
This Study	*Tyne*	*2198*	*2.37*	*0-100*
Shotton, 1978	Avon	1870	0.50	0-3000
Brennan & Macklin, Unpubl.	Swale	550	0.53	0-130
Macklin, 1985	Axe	31	0.54	0-312
Brown & Barber, 1985	Ripple Brook	19	0.05	0-2500
Brown, 1983	Stour	620	10.20	Max. depth of overbank deposition, 1979 flood
Macklin & Newson, Unpubl.	Swale	550	13.00	Max. depth of overbank deposition, 1986 flood
Lambert & Walling, 1987	Culm	276	0.05	Average overbank sediment ation, 1983-1984

Table 4.3 Fine-grained vertical accretion rates in selected British rivers

be the major causative factor. Close examination of the few British river basins in which longer-term fine-grained sedimentation rates have been estimated show most are underlain by shale or clay lithologies where alluvium has been deposited overbank rather than within-channel as at Low Prudhoe. This, together with divergent catchment land-use histories, may explain the generally low floodplain sedimentation rates recorded in the silt and clay suspended load rivers of lowland southern England (e.g. lower Severn, Avon, Ripple Brook, Culm) compared with much higher rates found to be more typical of river systems developed on sandstone lithologies in northern Britain (e.g. Swale and Tyne).

Variations in rates of vertical accretion have important implications for the preservation of the alluvial stratigraphic record of floods; high rates of deposition would appear to be essential for detailed preservation of flood-related bedding structures and units. At floodplain sites with low rates of deposition these features would tend to be destroyed by bioturbation and pedogenic processes (demonstrated by incorporation and mixing of recent, e.g. 1986, flood sediments at Low Prudhoe).

Conclusions

From a methodological viewpoint this study has demonstrated the utility of floodplain stratigraphic analysis in the reconstruction of flood frequency in the River Tyne: textural discontinuities in fine-grained vertically accreted sediments at Low Prudhoe provide a detailed, but partial, record of floods in the lower Tyne Valley between c.1890 and 1947. Although trace metal dating has enabled the timing of floods to be determined in detail, precise flow discharge estimates are problematic. While there appears to be a systematic relationship between flow magnitude and the size and thickness of flood units, the sedimentary flood record at Low Prudhoe has also been strongly influenced by variations in sediment supply and relative surface elevation (due to entrenchment of the channel) over the period of investigation.

The identification of systematic differences between sedimentary and documentary based estimates of flood frequency in the lower Tyne highlights the contribution fluvial geomorphology can make to developing and refining historical flood information. The Low Prudhoe study reveals an important source of non-stationarity that may affect flood series; changes in river bed and floodplain sedimentation levels that alter the flood carrying capacity of a channel, and therefore the frequency of inundation and flood hazard at a site. This is an important second order effect when considering the non-stationarity introduced by climatic change and to a large extent invalidates using floodstones to accurately calculate discharges and return periods of extreme floods.

Chapter 5

UPLAND FLOOD HISTORIES AND RECENT VALLEY FLOOR DEVELOPMENT: THINHOPE, WHITEWALLS AND KNAR BURNS

Introduction

This chapter considers geomorphological and sedimentological approaches to historic flood studies through an investigation of coarse flood sediments, deposited in the last 300 years or so, in 3 upland tributaries of the River South Tyne. It has three principle aims: 1. to date flood sediments and to evaluate their mode of deposition, 2. to establish the magnitude and frequency of geomorphologically "effective" floods and assess how this might relate to climate, vegetation and land-use changes, and 3. to examine the role of floods in longer-term valley floor development viewed in the context of Holocene environmental changes in the British uplands.

Study sites

Three headwater streams were chosen for study: Whitewalls Burn (NY 778525, 546-240 m O.D., drainage area 8 km^2), a tributary of the West Allen River, and Thinhope Burn (NY 680550, 595-180 m O.D., drainage area 12 km^2) and Knar Burn (NY 675532, 656-200 m O.D., drainage area 20 km^2) tributaries of River South Tyne which drains the north west part of the Northern Pennines (Fig. 5.1). All 3 sub-catchments are underlain by similar geologies (interbedded Carboniferous sandstones, limestones and shales), with river channels inset within Pleistocene and Holocene river gravels or pre-Quaternary bedrock. Whitewalls, Thinhope and Knar Burns are typical of many boulder- and cobble-bed streams draining moorland catchments in the Northern Pennine uplands in having steep gradients (<1 - <10 %), moderate to high yearly precipitation (c.1400 mm y^{-1} at Alston, NY 718465),

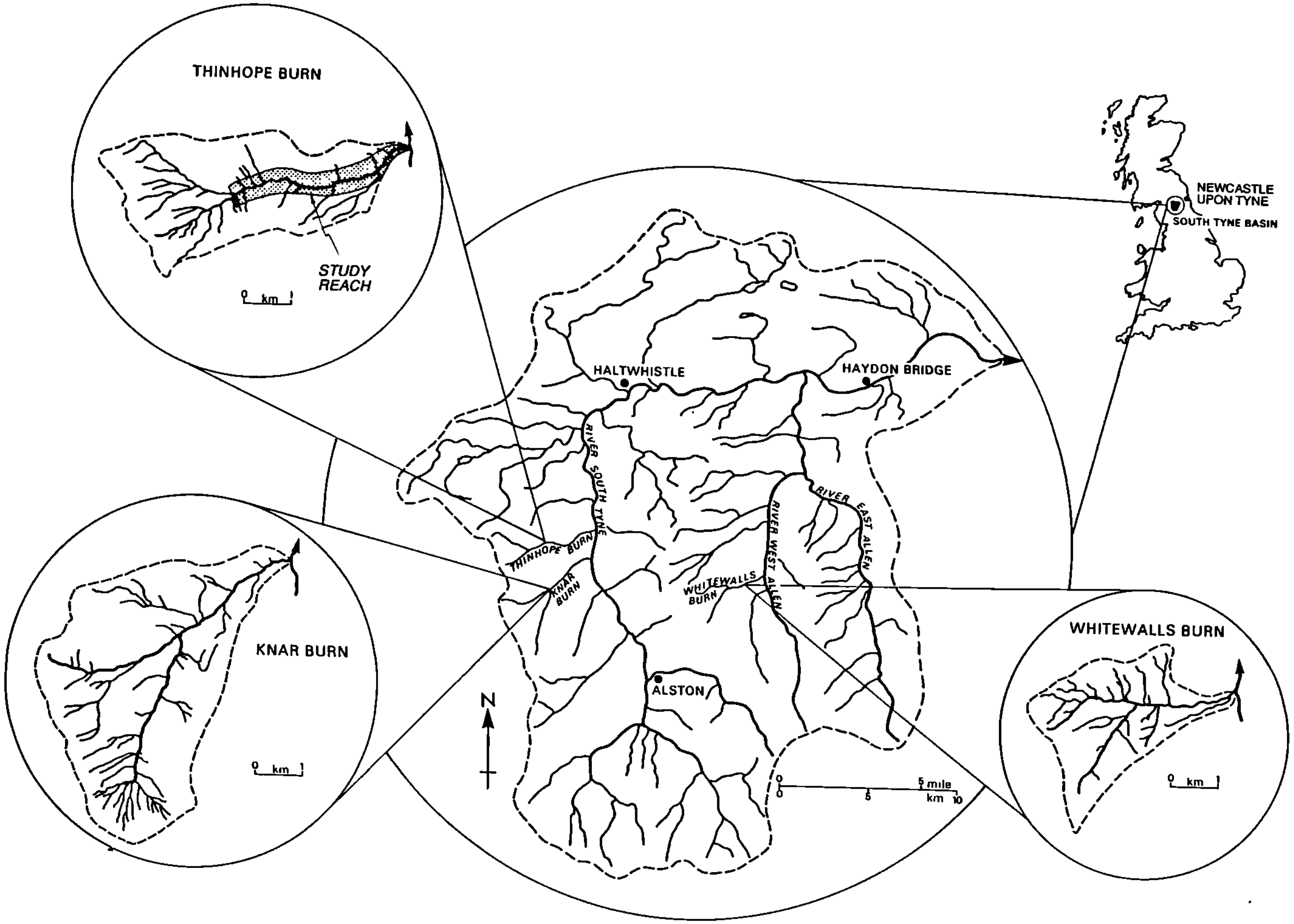


Figure 5.1 Location map showing stream networks and catchments of Knar Burn, Thinhope Burn and Whitewalls Burn. The 4.1 km study reach in Thinhope Burn is indicated

and flashy runoff regimes. Extensive cobble and boulder flood deposits form prominent terraces in all three catchments. They are particularly well-developed in Thinhope Burn, however, and this catchment was chosen for detailed investigation.

Methods

The morphology, sedimentary properties and sequence of recent flood deposits and earlier Holocene alluvial units in Thinhope Burn were established along a 4.1 km reach by morphological mapping and levelling (Fig. 5.2), using enlarged O.S. 1:10,000 maps and aerial photographs as a base. In addition, intermediate axes of the ten largest clasts were measured in at the surface of every flood deposit (66 locations in total) as a basis for estimating flow competence. Detailed logging and fabric analysis of coarse flood deposits was also carried out at a number of river bank sections in order to evaluate the Newtonian or non-Newtonian character of flood flows. Recent (last 250 years) coarse flood sediments in all three catchments were dated using lichenometry (Beschel, 1950; 1973; see below) and earlier historic and Holocene alluvial units in the Thinhope Burn catchment were dating using ^{14}C and pollen analysis.

Lichenometric dating of coarse flood sediments

Although lichenometry is a well established dating technique in glacial geomorphology (Beschel, 1961; Bergström, 1954; Matthews, 1974; Webber and Andrews, 1973) its application in fluvial studies is more limited, despite being shown by a number of workers in northern Britain (Harvey et al, 1984; Innes, 1983; Macklin, 1986) and Iceland (Thompson and Jones, 1988) to be particularly useful in providing a chronological framework for the deposition of coarse-grained alluvium. The technique is based on the assumption that the size of lichens present on a substrate is directly related to the time elapsed since its exposure, assuming that the substrate (coarse flood sediments in this case) was initially devoid of lichens and colonised very shortly after deposition. Coarse flood sediments in

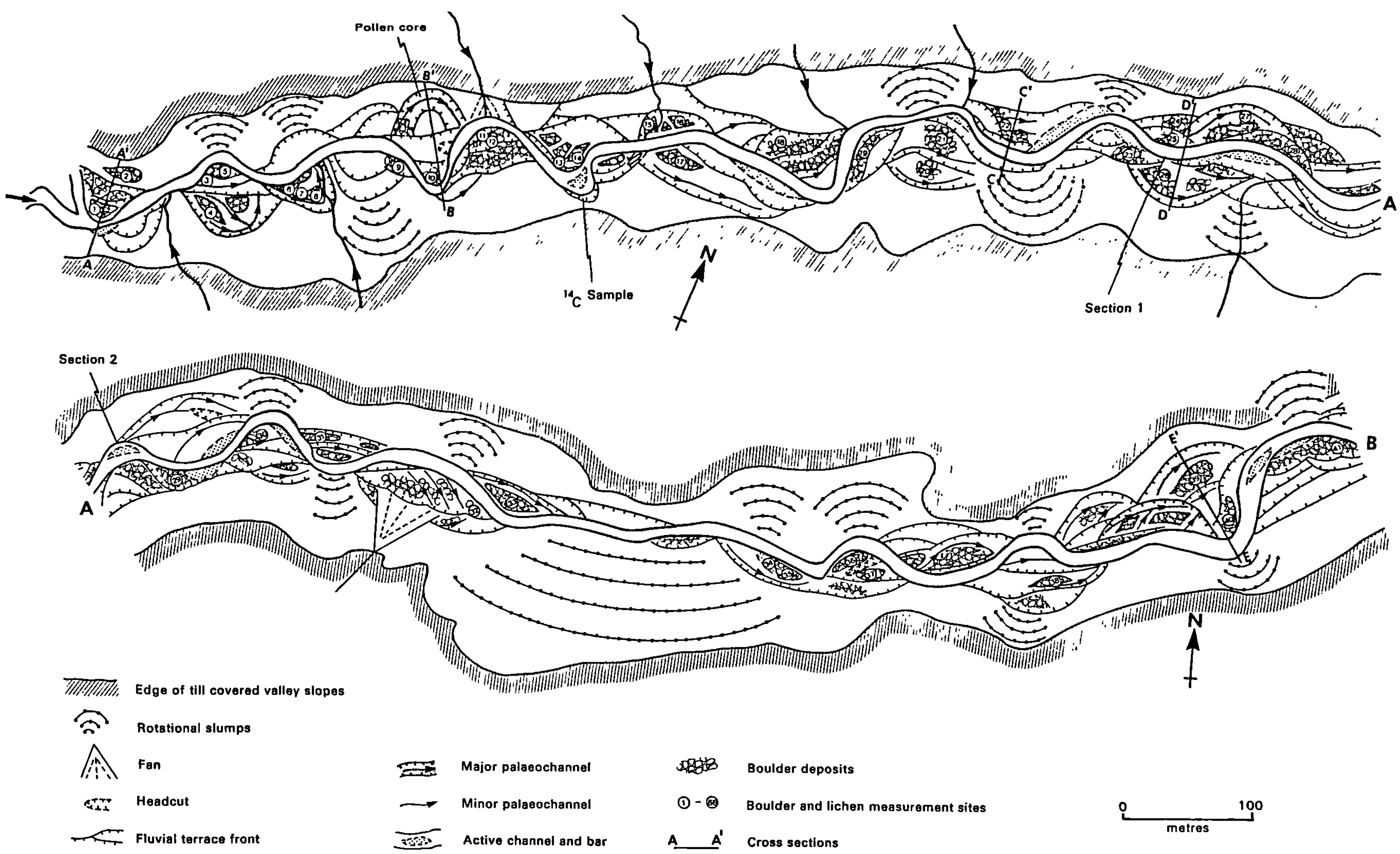
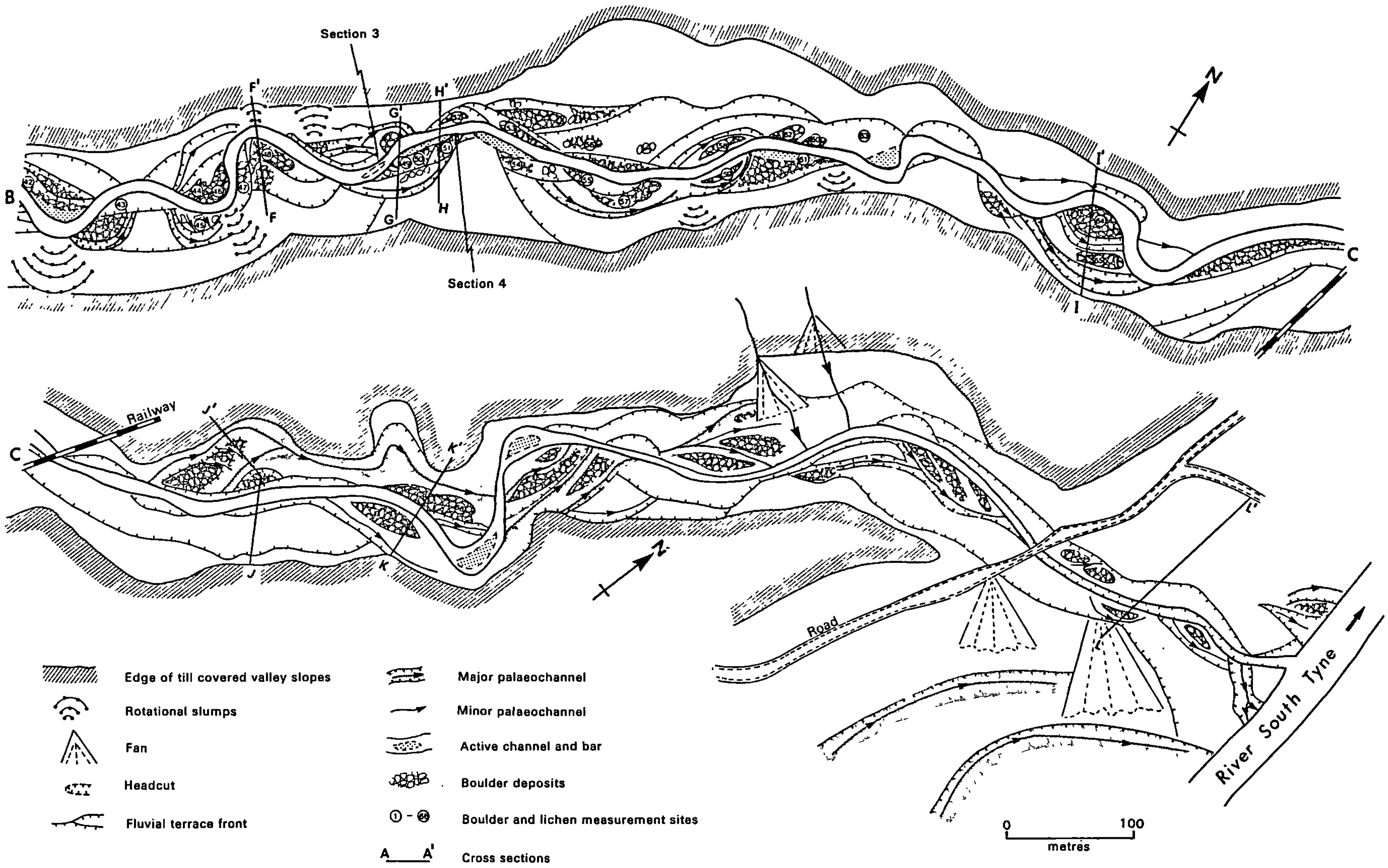


Figure 5.2 Morphological map of Thinhope Burn showing valley floor terraces, palaeochannels, alluvial fans, boulder flood deposits and valley side rotational landslips. The position of surveyed cross-sections, boulder and lichen measurement sites, logged river bank sections, pollen and ^{14}C sample locations are marked



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headwater tributaries of the South Tyne appear to comply with both assumptions. Firstly, lichens are clearly visible on sediments observed to have been deposited by a major flood in August 1986, indicating that there is a short colonisation lag (<2 years). Secondly, reworking of older flood sediments can easily be recognised by anomalously large lichens evident on a restricted number of clasts or rock surfaces. These lichens were excluded from age analyses.

Two crustose lichens were used for this study that were abundant in the study area; *Huilia tubercolosa* and *Rhizocarpon geographicum* agg. Identification of *Huilia tubercolosa* was facilitated by use of a solution of potassium iodine and iodide that stains the thallus a purple colour (Graham, pers. comm.). A range of environmental and site factors have been found to influence rates of lichen growth including aspect and altitude (Armstrong, 1975; 1977) and substrate lithology (Gregory, 1976; Innes, 1983). Neither aspect or altitude were found to have a significant effect on lichen size in the study area (Table 5.1). Flood deposits in Thinhope, Whitewalls and Knar Burns consist mainly of Carboniferous sandstone boulders and cobbles, and therefore lichen measurements used both to construct age-size curves, and date flood sediments were restricted to this lithology. Over 250 measurements, on tombstones and bridges at 18 sites in the South Tyne catchment, were used to construct age-size curves covering a 250 year period back to c. 1760 A.D. (Fig. 5.3). Each point of the age-size plots represents the mean of the 3 largest lichens (the longest axis measured to +/- 0.1 mm) present on dated substrates. *Rhizocarpon geographicum* agg. in the Northern Pennines has a curvilinear growth curve similar to that recorded in other parts of northern England (Harvey et al, 1984) and Scotland (Innes, 1983). The growth rate of *Huilia tubercolosa*, however, is more rapid and linear in form. Regression lines fitted to the age-size data represent an empiracally-derrived relationship between surface age and thallus long-axis for a well-defined sample (cf. Kugelmann, 1991; Mottershead, 1980) and as such are not directly comparable to lichen growth curves developed for other areas. The

Variable	*R. geographicum* agg.		*H.tubercolosa*	
	r	n	r	n
AGE	0.889*	32	0.907*	53
ALTITUDE	-0.294	31	0.232	53
ASPECT	0.327	21	0.284	36

r correlation coefficient
n sample number

* values significant at 99 %

Table 5.1 Correlation between lichen thallus diameter and selected variables

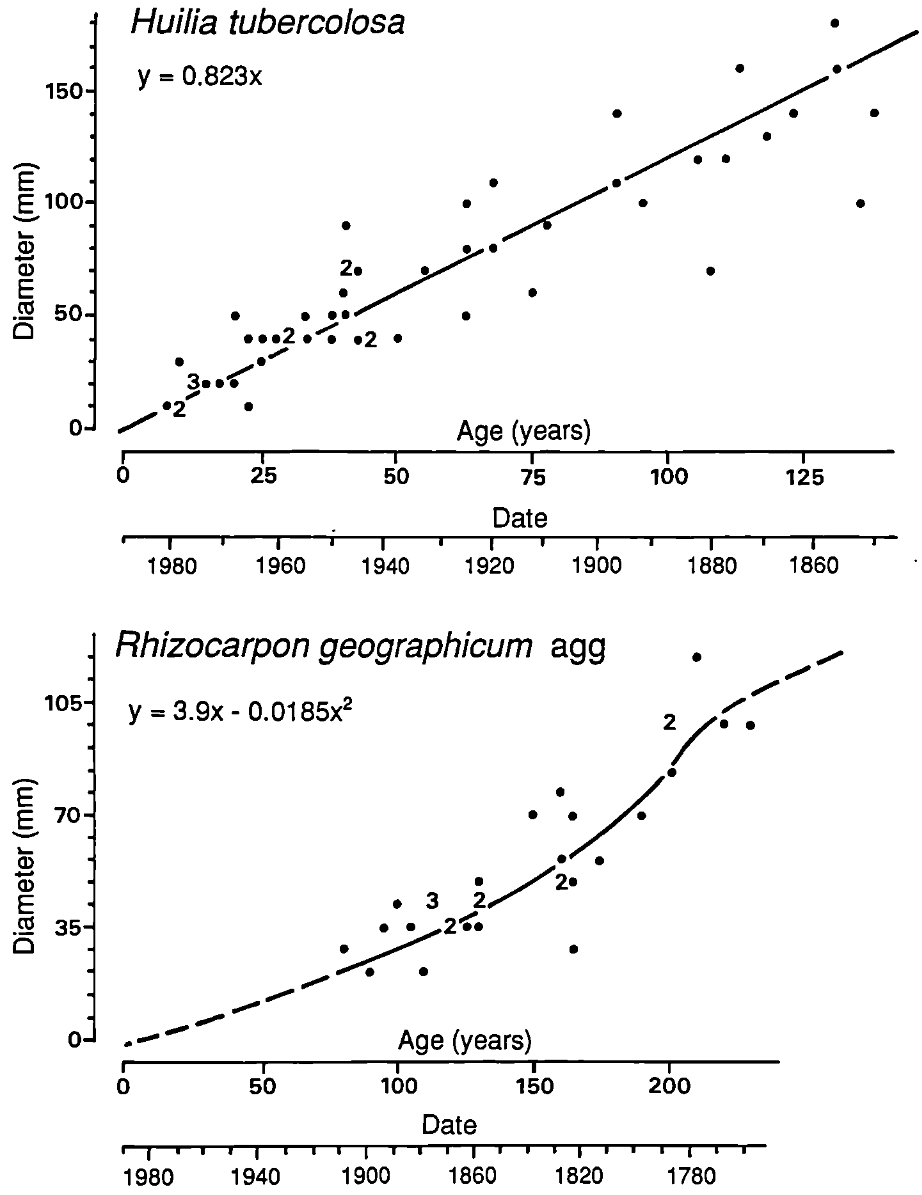


Figure 5.3 Age-size curves for *Huilia tubercolosa* and *Rhizocarpon geographicum* agg.

general validity of the age-size relationship was confirmed by dating a number of control surfaces of known age (Table 5.2).

The age of flood events was estimated from the average of the 3 largest thalli of *Rhizocarpon geographicum* agg. and/or *Huilia tubercolosa* growing on the surface of large cobbles and boulders that formed flood deposits (see Figs. 5.2 and 5.4). By using two lichen species with different growth rates it was also possible (where both lichen species were present) to cross-check estimates on flood deposits between 75 and 120 years old (Table 5.3). Post-depositional re-working of flood deposits is limited in Thinhope Burn as high rates of channel bed incision restrict subsequent inundation. Gregory (1976) suggested that inundation frequencies of greater than once in 2 years are required to destroy lichen cover. Flood units deposited at valley-floor locations in the study area are not inundated sufficiently frequently for lichen growth to be inhibited.

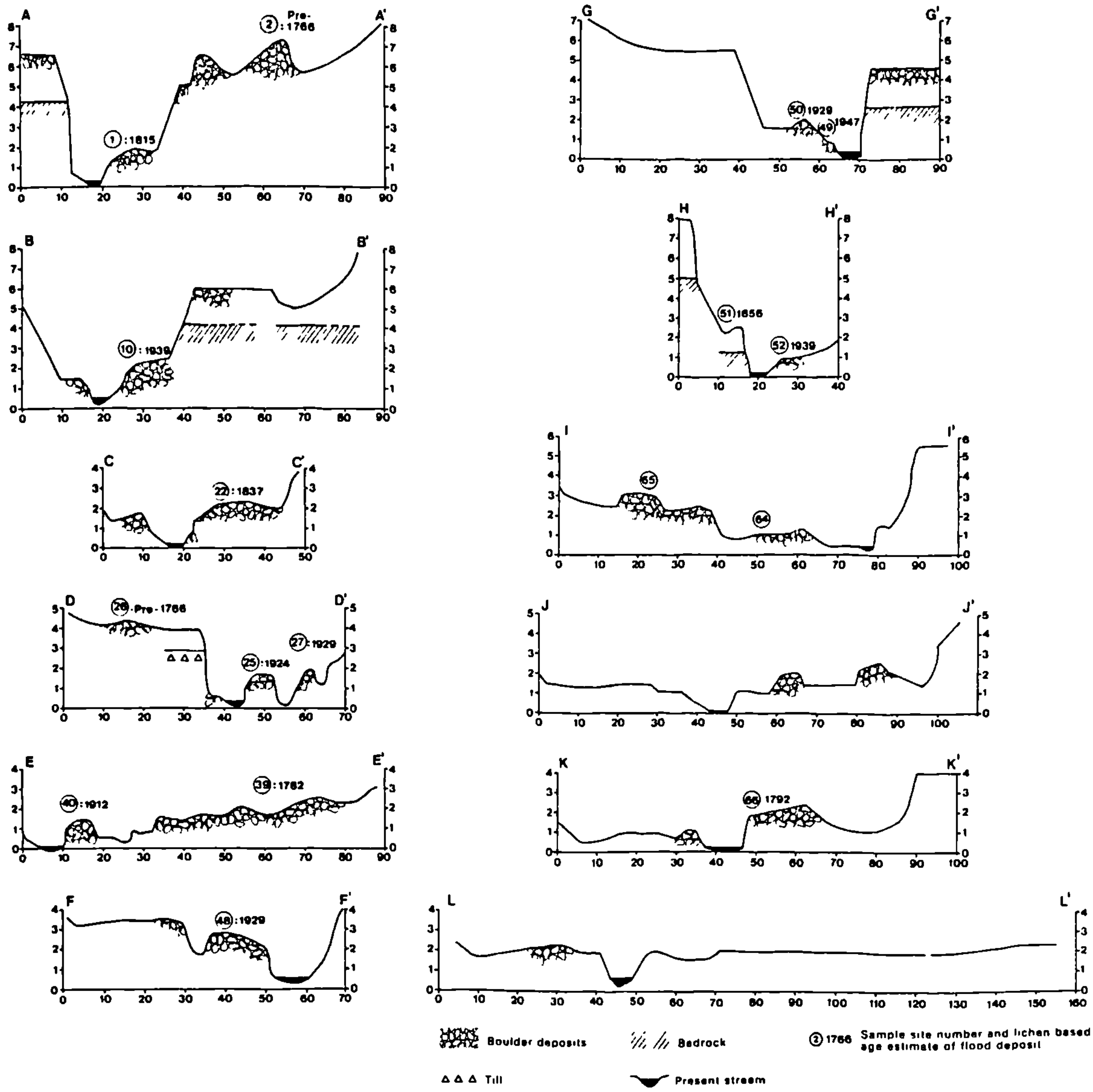
Geomorphic, sedimentologic and hydraulic properties of Thinhope Burn flood deposits

On the basis of their morphology and sedimentary properties (sediment size, fabric and matrix content, Fig. 5.5) flood deposits in Thinhope can be broadly divided into five types: cobble-boulder bars, splays and sheets, and boulder berms and lobes. Bars, splays and sheets comprise over 80 % (by number) of recent flood deposits in Thinhope and are present throughout the length of the valley, whereas berms and lobes make up only a minor proportion (<15 %) and are restricted to the upper reaches of the catchment. Flood deposits are generally located in wider and lower gradient reaches, most frequently on the inside of valley meander bends. There are few deposits in straight and steep reaches where channels are confined by soliflucted till or bedrock.

Nature of Substrate	Actual Date	Lichen Type	Size* (mm)	Pred[1] Date
Enclosure walls	c.1800	*R.geographicum* agg.	78.7	1797
"	c.1800	*R.geographicum* agg.	74.3	1801
Coarse-grained channel sediments	post-1860	*R.geographicum* agg.	40.0	1863
"	post-1860	*H.tubercolosa*	72.0	1930

* measurements based on mean of the 3 largest lichens
1 predicted date

Table 5.2 Predicted lichen dates for surfaces of known age



<u>Figure 5.4</u> Surveyed cross-sections of Thinhope Burn showing valley floor morphology and age-height relationships of flood deposits

Nature of Substrate	Lichen species and size (mean of 3 largest, mm)	Predicted Date
Drystone wall, repaired 1978	*R.geographicum* agg. *H.tubercolosa*	1978 1977
Flood Deposit, no. 11	*R.geographicum* agg. *H.tubercolosa*	1939 1939
Flood Deposit, no. 19	*R.geographicum* agg. *H.tubercolosa*	1937 1938
Flood Deposit, no. 32	*R.geographicum* agg. *H.tubercolosa*	1927 1930

Table 5.3 Cross-check of lichen dates for flood deposits and surfaces with both lichen types present

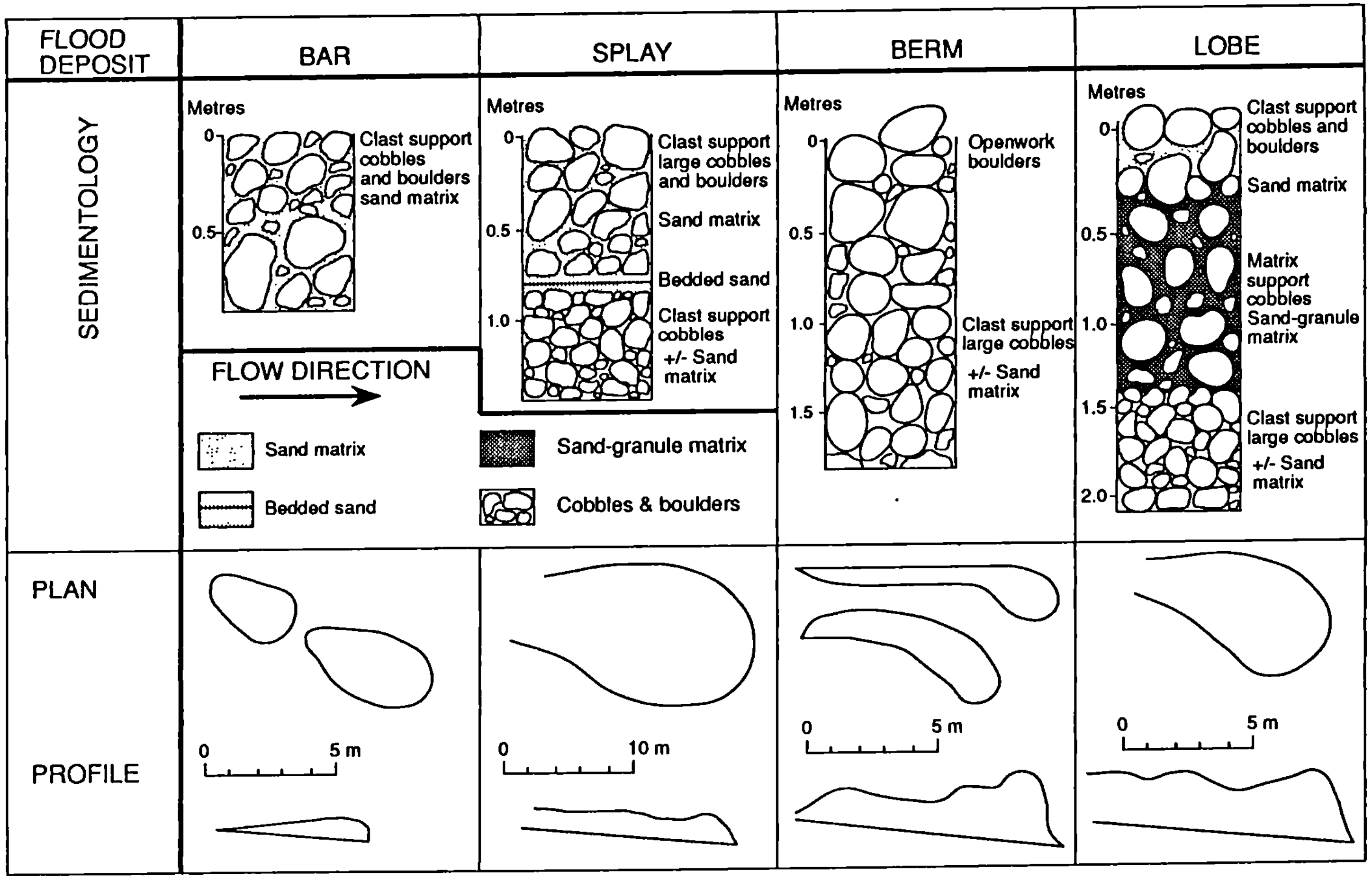


Figure 5.5 Morphological and sedimentary properties of coarse-grained flood deposits in Thinhope Burn

Cobble-boulder splays and sheets

Splays form broad features (e.g. Deposit 39, Fig. 5.4, 50 m wide), generally less than 1 m thick with low surface relief (<0.5 m), and are either flat-topped (e.g. 4-5 m right bank terrace, cross-section G-G', Fig. 5.4) or have slightly convex boulder-covered surfaces (e.g. Deposit 22, Fig. 5.4). Cobble sheets are usually thinner (typically only one clast thick) and have lobate margins with "fingers" of pebble-size material extending downstream (e.g. Deposit 57, Fig. 5.2). Concentration of coarse material at the downstream end of splays and sheets produces deposits with well-defined downstream limits, while upstream margins are generally more diffuse. Flood splay deposits are comprised of stratified layers of clast-supported cobbles and boulders with a sandy matrix (Fig. 5.6), and occasionally include layers of bedded sand (Fig. 5.5). Splay and sheet deposits show weak to strong imbrication (average dips 51°) with A-B planes aligned transverse to the direction of flow.

Cobble-boulder bars

Cobble and boulder bars have low to moderate relief (c.0.5 m), are up to 1.5 m thick (e.g. Deposits 19 and 58, Fig. 5.2), typically linguiform and fine downstream. They are comprised of imbricated clast-supported small boulders and cobbles, sometimes with a sandy matrix, and in section exhibit both normal or reverse grading (Fig. 5.5). A-B planes are generally aligned transverse to flow, with higher dips averaging 55°-60°) than splay deposits.

Boulder berms

Berms have relatively high surface relief (up to 1 m), steep sides and can be more than 2 m thick (e.g. Deposit 2, cross-section A-A', Fig. 5.4). In plan (Fig. 5.4) they are usually curved, streamlined, aligned parallel to flow direction, and fine downstream. They have high length:width ratios and strongly convex upper surfaces which are moderately well imbricated with steeply dipping A-B planes (mean dip 60) aligned both parallel and transverse to flow (e.g. Deposit 2, Figs. 5.2 & 5.4).

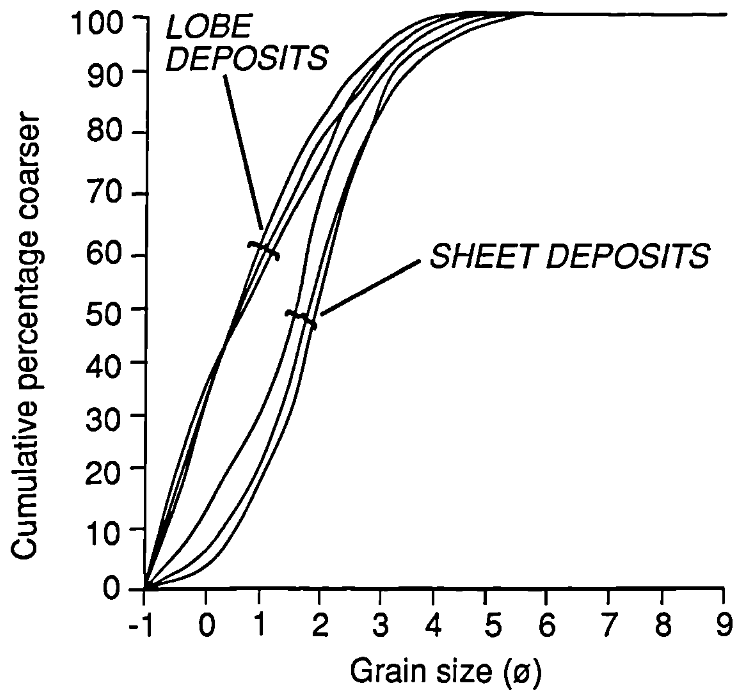


Figure 5.6 Comparison of grain-size curves for matrix sediments in lobe and sheet/splay flood deposits

Berms consist of open-work clast-supported boulders (some with B axes up to 1.5 m) that display weak horizontal stratification and are reversely graded. Their surfaces are characteristically pitted by small depressions which appear to have formed as the result of dewatering and collapse of loosely packed fabric shortly after deposition.

Boulder lobes

Boulder lobes form the thickest flood deposits in Thinhope (c.2 m). Their surfaces are convex, but flatter than berms and in plan lobes are straighter and have lower length:width ratios (e.g. Deposit 48, Figs. 5.2 and 5.4). They are more poorly sorted than berms and have a greater matrix content. Fig. 5.5 illustrates a typical boulder lobe sequence: horizontal stratification is usually evident with alternating layers of cobble or boulder-size sediments. Matrix content (Fig. 5.6) increases with depth and the lower part of some deposits are matrix-supported (e.g. 1.4-2 m of section 1, Fig. 5.5). Boulder lobes have weaker fabrics than berms with A-B planes aligned both parallel and transverse to flow, weak imbrication and variable dips (between 30° and 70°).

<u>Hydrodynamic interpretation and environment of deposition of flood sediments</u>

Coarse flood deposits (typically comprised of clast-supported cobbles and boulders with both reverse and normal grading) similar to the bars, splays and sheets in this study, have been described in a number of steep river systems in both the U.K. (Carling, 1986, 1987; Wells and Harvey, 1987) and U.S.A. (Krumbein, 1942; Scott and Gravlee, 1968; Stewart and LaMarche, 1967). They have been considered to be the product of high energy Newtonian water floods (Carling, 1986; Costa, 1988).

Deposits whose morphological form and sedimentary sequence resemble boulder berms and lobes in Thinhope have been attributed to flows with high sediment loads, variously termed debris-torrents (Miles and Kellerhals, 1981), bedload (Iseya et al, in press) and hyperconcentrated flood (Pierson and Scott, 1985; Scott, 1988) flows. These, in terms of bulk density and shear strength, are intermediate between stream and debris flows and may be Newtonian or transitional in character depending on sediment concentration (Costa, 1988). Relatively well developed imbrication, moderate sorting and open-work texture of boulder berms in Thinhope however, are sedimentary properties more consistent with Newtonian flows (Costa, 1984). This is supported by the findings of Carling (1989) who has demonstrated Northern Pennine streams, which have relatively low concentrations of silt and clay at high discharges (<100 mgl^{-1}), are still Newtonian even with gravel concentrations up to 50 %. Methods of boulder lobe deposition, however, are not so clear. Whilst some lobes exhibit weak horizontal and inclined stratification that suggest Newtonian conditions others have matrix-supported coarse clasts in massive beds with extremely poor sorting and reverse grading more typical of non-Newtonian flows. Deposition can be envisaged by rapid grain-by-grain accumulation of material from suspension and traction under flows with high loads of both coarse and fine sediment (Iseya et al, in press; Smith, 1986). These flows can be considered as "quasi Newtonian" with turbulence the primary support mechanism, although high concentrations of finer sediment, by increasing viscosity and buoyancy and grain interactions, contribute to the support of the larger clasts (Scott, 1988). While these flows do not possess the shear strength of debris flows, viscosity is sufficient to allow boulder lobes to build up to greater thicknesses than would be possible by water floods with lower sediment concentrations.

The distribution of different types of flood deposit in Thinhope appears to closely reflect local variation in sediment supply. Splays, sheets and bars, deposited from flows with the lowest sediment concentrations, are widely distributed throughout the length of the valley. Boulder berms and lobes, however, are located immediately downstream of major sediment sources (e.g. rotational land-slips and tributary junctions) and are only found in the upper reaches of Thinhope where slumping of soliflucted till into the channel provides abundant coarse and fine material.

Flood frequency and magnitude reconstruction, 1766 to the present

1. Age of flood deposits and large flow frequencies

In Thinhope 21 flood events during which significant transport of boulder size material occurred have been identified. All but one event has been dated by lichenometry (Fig. 5.7) and everyone can be attributed to floods recorded in archive sources over the period 1766 to the present (Brand, 1789; Jones et al, 1984; Latimer, 1857; Sykes, 1866). The oldest coarse flood unit is represented by a number of deposits located on terraces 4-6 m above the present river bed (e.g. Deposits 2 and 26, Fig. 5.4). Although large *Rhizocarpon geographicum* agg. are present on boulder surfaces, thalli are fragmented and appear to have passed beyond their "great" period of growth which in the Northern Pennines approaches 230-250 years. This would indicate that the sediments relate to a major flood that occurred sometime before c.1760. Deposits from this flood event overlie peat ^{14}C dated to 1161 +/- 60 cal BP, 788 A.D. (Beta-33435) which provides a terminus post quem for this unit.

In Fig. 5.8 the number of dated floods per decade in each catchment are plotted. Several general patterns emerge from this, with distinct clustering of floods centred in the periods 1780-1820, 1840-1880 and 1920-1950. Precipitation measurements from Durham observatory (Harris, 1985) and gauges in the Tyne catchment (Fig. 3.6) together with proxy climate data derived from archive records and raised mires in the region (e.g. Barber, 1981; Lamb, 1977), show that these were periods of increased rainfall and wetness in northern England. They also correspond with phases of increased runoff in a number of European rivers (Probst, 1989; Probst and Tardy, 1987) and suggests that the timing of floods in the upper South Tyne between c.1766-1960 follow major hydroclimatic fluctuations over the same period in Western Europe.

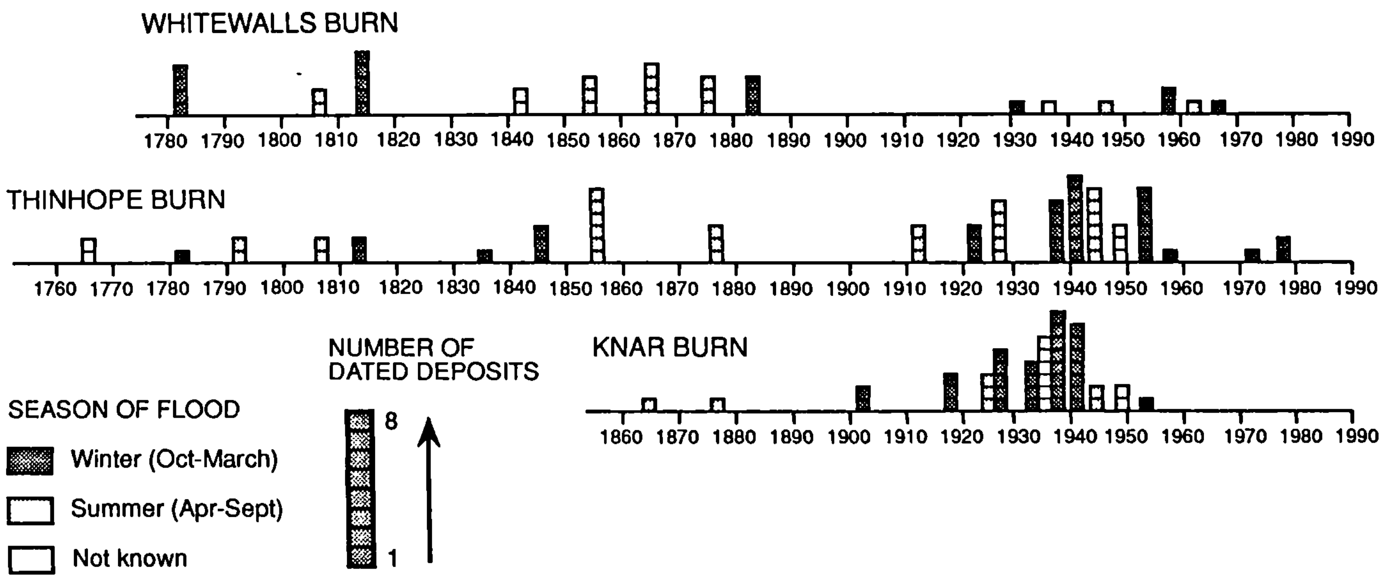


Figure 5.7 Lichen dated flood events (1766-1980) in Whitewalls Burn, Thinhope Burn and Knar Burn catchments

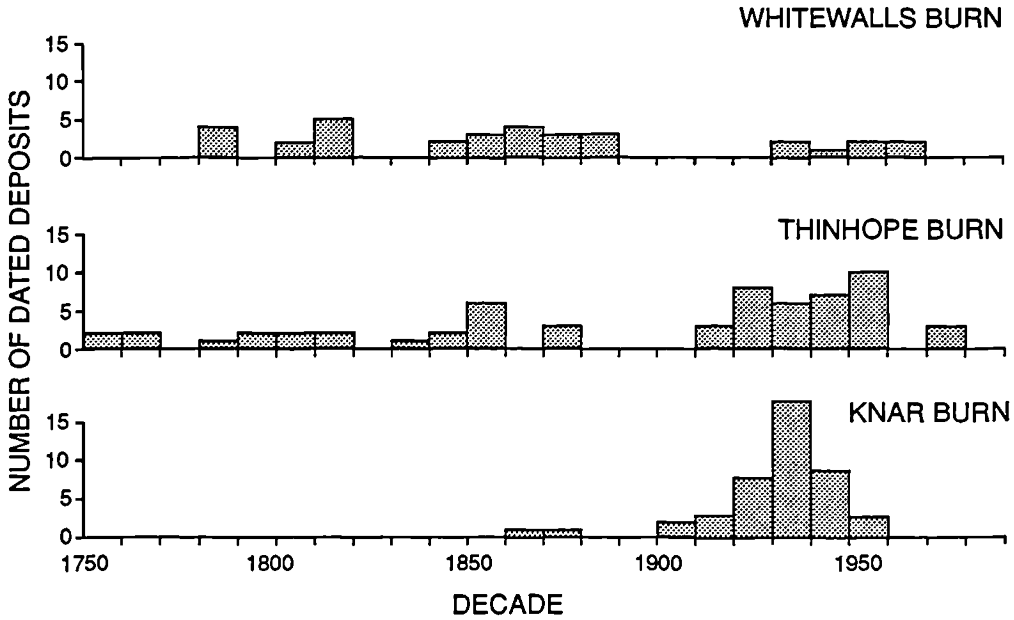


Figure 5.8 The number of dated flood events per decade in the study catchments

2. Discharge estimates of large rare floods

B axes measurements of the ten largest boulders in each flood deposit (Appendix IV) were combined to find the mean largest boulder size for 21 dated flood events from 1939 to before 1766 in Thinhope Burn (Appendix V). Notwithstanding the limited accuracy and precision of flow competence equations in palaeohydraulic reconstruction (e.g. Bathurst, 1987; Komar, 1989), four well established flow competence equations (Table 5.4), developed on, or tested with data from, gravel/boulder-bed rivers, were used to provide an envelope of possible discharges. Analysis was restricted to flood units located at surveyed cross-sections, and excluded boulder lobes given that flow competence equations employed assume Newtonian flow conditions.

A very wide range of values (Fig. 5.9 and Appendix V) emerge from this analysis and a number of factors appear to complicate a straightforward interpretation of discharge reconstructions. Flow widths at cross-sections were based on flood deposit width and should be considered as minimum estimates, given that both the extent of post-flood erosion and the proportion of the valley floor inundated during an event are unknown. Similarly, flow depths were based on flood deposit depth. Other complications were largely a result of the wide size distribution of sediment available in Thinhope Burn. Equation 1 (Bathurst, 1988), based on a modified Schocklitsh approach, attempts to account for selective entrainment from a mixed-size channel bed by including a measure of relative clast protrusion (d_i/d_r, where d_i is particle diameter and d_r is reference particle diameter) in flow competence calculations. Determination of the reference particle diameter (d_r) is, however, difficult due to horizontal sorting and vertical armouring of sediments (Komar, 1989), and values of d_r that are too large will greatly overestimate discharge. For Thinhope, discharge estimates based on a d_r calculated from the d_{50} of the current channel bed (1a) were considerably lower than those using a d_r calculated from the d_{50} of historic flood sediments (1b). Equation 2 (Carling, 1986) is an empirical approach based on data collected by Carling (1983)

Reference	Discharge Equation
1. Bathurst (1988)*	$Q = Wq_{ci}$
	$q_{ci} = q_{cr}(d_i/d_r)^b$
	$b = 1.5(d_{84}/d_{16})^{-1}$
	$q_{cr} = 0.15g^{0.5}d_r^{1.5}S^{-1.12}$
2. Carling (1986)	$Q = 306Ad_i^{-2/9}S^{-1/6}n^{-1}$
3. Williams (1983)	$Q = \frac{wW}{\$S}$
	$w = 0.079d_i^{1.3}$
4. Williams (1983)	$Q = VDW$
	$V = 0.17d_i$

*	(1a)	d_r estimate based on d_{50} of active stream-bed sediments
	(1b)	d_r estimate based on d_{50} of historic stream sediments

Notation

A	cross-sectional area
b	exponent
D	depth
d_i	particle size diameter
d_r	reference particle size diameter
$d_{84}(d_{16})$	particle size diameter for which 84(16)% are finer
g	acceleration due to gravity
n	roughness coefficient
s	slope
Q	water discharge
q_{ci}	critical water discharge for movement of d_i
q_{cr}	critical unit discharge for movement of d_r
V	mean flow velocity
W	width
$	specific weight of water
w	stream power per unit channel width

Table 5.4 Flow competence equations used to estimate flood discharges in Thinhope Burn

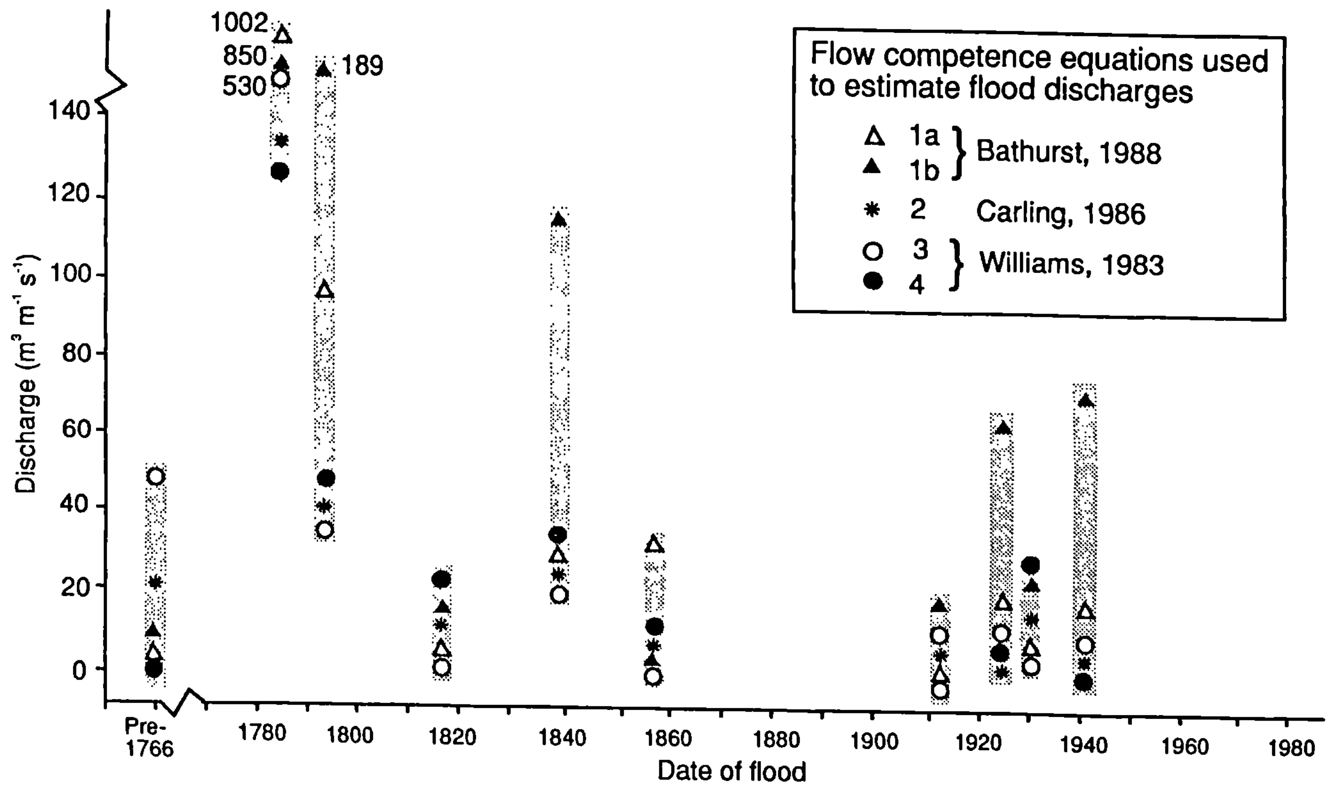


Figure 5.9 Discharge estimates for historic floods in Thinhope Burn

in Great Eggleshope Beck, upper Teesdale. This stream is very similar to Thinhope and it was anticipated that Carling's equation might provide the most appropriate discharge estimates. Equations 3 and 4 are semi-empirical relationships from Williams (1983) based on envelope curves fitted to a range of published sediment transport studies and provide minimum estimates of discharge.

Notwithstanding both practical and theoretical limitations to flood discharge reconstruction outlined above, some general but systematic patterns do emerge. Older flood events in Thinhope have the largest estimated discharges, especially those of 1782, 1792 and 1837. Between 1837 and 1924 flood estimates are lower, thereafter, in the period 1924 to 1940, flood magnitudes increase but are smaller than late eighteenth century floods.

Table 5.5 estimates return periods of these floods (using equation 2 discharge estimates), calculated following established procedures for ungauged catchments outlined in the Flood Studies Report (N.E.R.C., 1975; Sutcliffe, 1978, Table 4). Floods before 1856 would appear to have very long recurrence intervals (>1000-300 years) while later floods have return periods approaching that of the mean annual flood. Stephens and Lynn (1978), however, have demonstrated that established regional growth curves in Britain may not be appropriate for calculation of flood return periods in small, steep upland catchments such as those in the Northern Pennines. They suggest the use of steeper curves in small upland tributaries which would result in significantly shorter predicted recurrence intervals for late eighteenth and early nineteenth century floods in Thinhope.

Boulder size in all dated flood deposits in Thinhope was also used as a proxy for flood magnitude (Fig. 5.10). This shows an apparent decrease in flood magnitude (boulder size) since the late eighteenth century though a number of large floods are evident between 1929 and 1954. The reduction in clast size within flood deposits in Thinhope since the end of the eighteenth century (becoming more pronounced after the 1954 flood) would appear to reflect, partly a real decrease in flood competence

Flood Date	Estimated Discharge[1] Q ($m^3 s^{-1}$)	Mean Annual Flood[2] $\hat{Q}$ ($m^3 s^{-1}$)	$Q/\hat{Q}$	Return Period[3] (years)
pre 1760	22.42	5.61	4.00	>1000
1782	135.75	9.21	14.74	>1000
1792	42.01	11.12	3.78	>1000
1815	14.33	5.61	2.55	300
1856	8.46	10.07	0.84	<2
1912	8.55	9.21	0.93	2
1924	8.40	7.84	1.07	3
1929	18.02	9.79	1.84	50
1939	5.60	10.07	0.56	<2

1 Based on equation 2 (Carling, 1986)
2 Following Flood Studies Report (Sutcliffe, 1978)
3 Using modified regional growth curves (Flood Studies Supplementary Report, 1983)

Table 5.5 Estimated discharges and return periods of historic large floods in Thinhope Burn

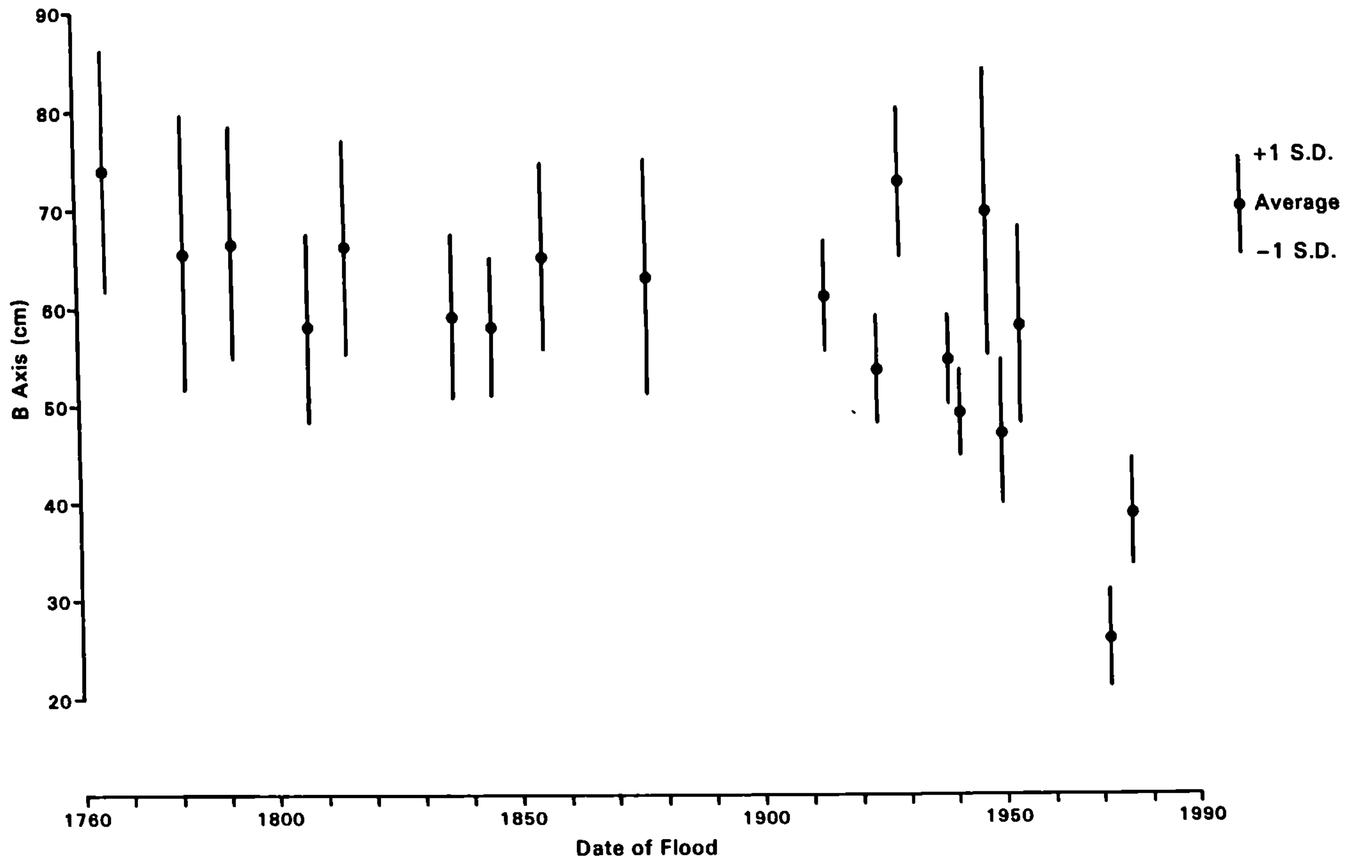


Figure 5.10 A plot of mean B axis size in Thinhope Burn flood sediments deposited between 1766 and 1977

over the last 200 years, but also change in the availability of very large clasts for stream transport. This has resulted from rapid and pronounced incision causing Thinhope Burn to become increasingly ensconced within its own alluvial fill, isolating it from till and bedrock that crop out on the valley sides which are the principal sources of large boulders. This inevitably sets a significant constraint on flow competence and magnitude estimates employing boulder size measurements in more recent (post 1960) flood events. Unusually large boulders in flood units dated to 1924 and 1947, however, would appear to reflect flood events where slope-channel coupling was temporarily re-established.

Floods and longer-term valley floor development

Over the last 1600 years or so the vertical tendency of Thinhope Burn has been one of incision (locally up to 8 m) separated by periods of relative stability and limited valley floor sedimentation. This sequence is especially clear in the upper reaches of the basin where three well developed cut and fill terraces are evident at c. 8, 6 and 4 m above the present stream bed (Fig. 5.11). The highest terrace (c.8 m) consists of gravel overlain by c.2 m of sands and silts which in the upper part of the unit, and towards the sides of the valley, interfinger with peat. ^{14}C dates of 8692 +/- 80 cal BP (Beta-37353) and 1577 +/- 50 cal BP (Beta-37352) from wood both within basal gravels, and at the interface between silts and peat (0.5 m below the surface of the terrace), respectively, indicate relatively slow valley floor alluviation in Thinhope Burn over much of the Holocene.

Sometime after 1577 cal BP (374 A.D.) the first major phase of Holocene valley floor incision occurred with up to 4 m of erosion. By around 1161 cal BP, 788 A.D. (^{14}C dates of wood at the interface between sands and peats in the 6 m terrace, Fig. 5.11), however, channel incision had ceased and limited valley floor sedimentation was taking place. A second major phase of incision after 1161 cal BP resulted in removal of earlier Holocene alluvial fills and Pleistocene glacial

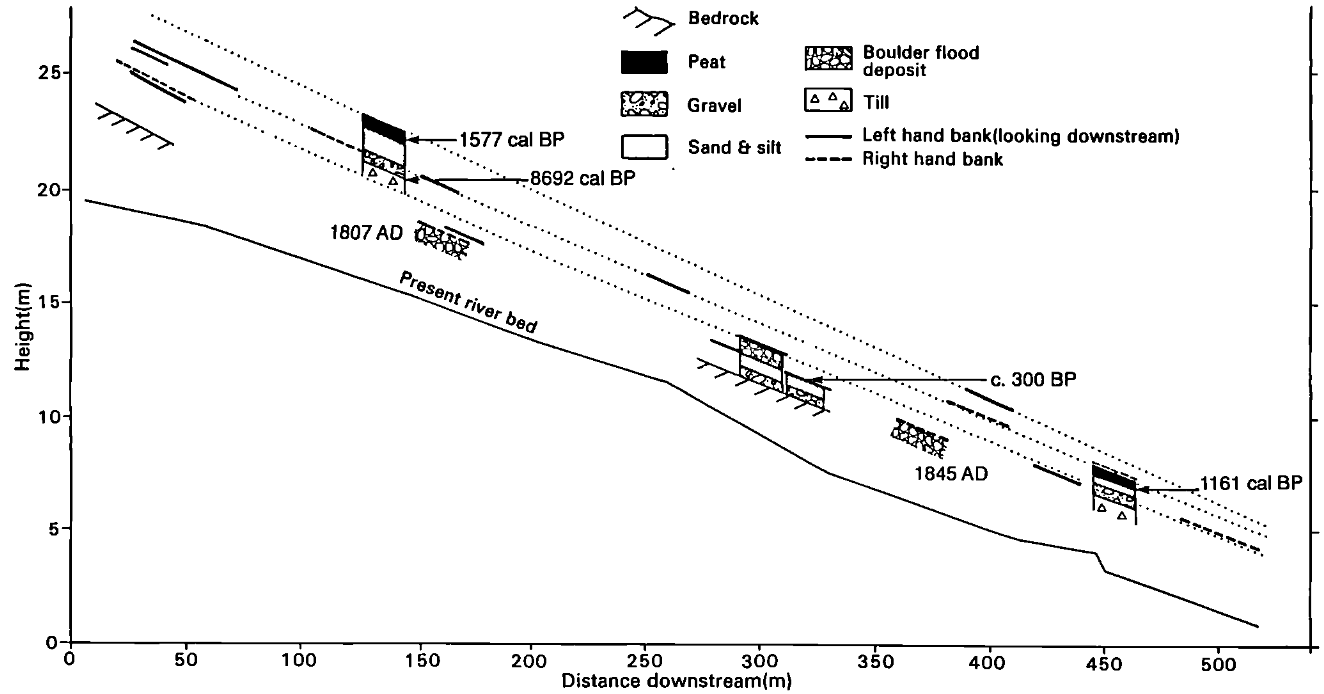


Figure 5.11 Surveyed longitudinal profile of 0.5 km reach in Thinhope Burn immediately downstream of the confluence of Faugh and Mardy Cleughs (Fig. 5.2). It shows the positions, heights and sequence of dated Holocene alluvial fills, boulder flood deposits and river terraces in relation to the present stream bed

sediments. Subsequent refilling of the valley bottom took place mostly with fine-grained alluvium to a level c.4 m above the present stream bed. This terrace is the most extensive in Thinhope and has on its surface a number of palaeochannels which are more sinuous and have lower width/depth ratios than the present channel. Pollen analysis of silts infilling one of these palaeochannels (cross-section B-B', Fig. 5.4; section 3, Fig. 5.5) shows a sequence (Heap, unpublished) very similar to that recorded by Roberts et al (1973) at Bollihope Sheill in nearby upper Weardale and ^{14}C dated to 1700-1780 A.D.. This would suggest that this channel was cut-off and began receiving fine sediment sometime at the turn of the seventeenth century.

The third, and most recent, major phase of incision was initiated possibly as early as the late seventeenth century and continues on a more limited scale to the present day. Over this period there has been up to 4 m of channel incision, locally through bedrock, that has produced a series of unpaired terraced coarse flood deposits (described previously) very different to earlier fine-grained Holocene alluvial fills in Thinhope. Lichenometric dating of levelled flood deposits enables both the timing and pattern of incision in the Thinhope catchment since 1766 A.D. to be examined in some detail (Fig. 5.12). This shows incision ended earlier downstream (c.1780 A.D.) than in upstream (c.1816 A.D.) reaches of Thinhope. In upper reaches of the catchment (Fig. 5.12B) limited aggradation in the early nineteenth century was followed by valley floor stability until 1940 when further incision occurred. In downstream reaches (Fig. 5.12C) between 1780 and 1860 A.D. channels were vertically stable, however, since the mid-nineteenth century, with exception of valley floor infilling by a series of floods in the 1930s, there also has been progressive incision.

A schematic summary of Holocene valley floor development since c.8500 cal BP in Thinhope is shown in Fig. 5.13. It is clear from this that in the late Holocene, most notably in the last 300 years, there has been a striking transformation of channel and floodplain sedimentation styles in Thinhope Burn, accompanied by

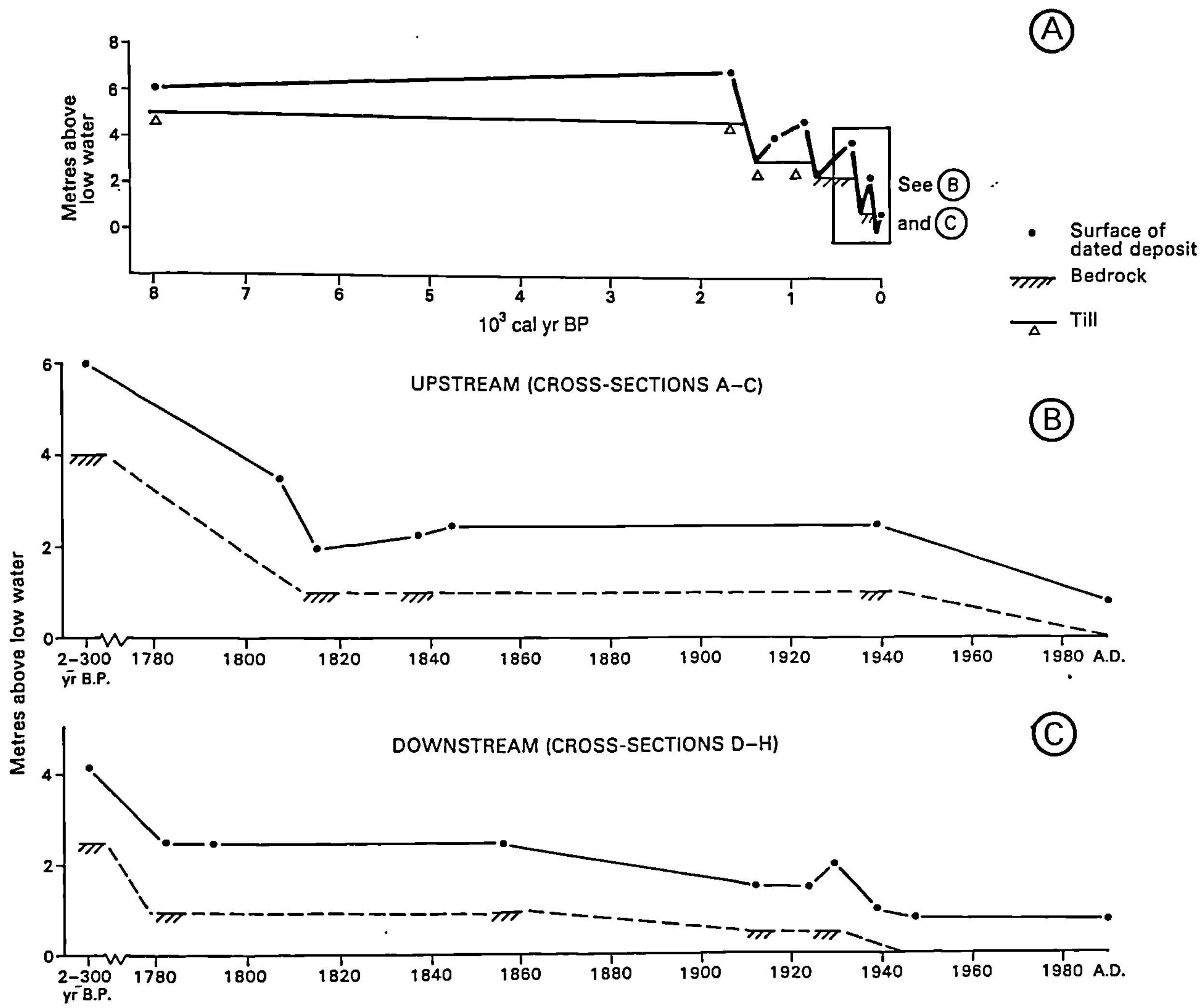


Figure 5.12 Time-level diagrams for Holocene alluvial units (A) and recent coarse flood deposits (B and C) in Thinhope Burn catchment

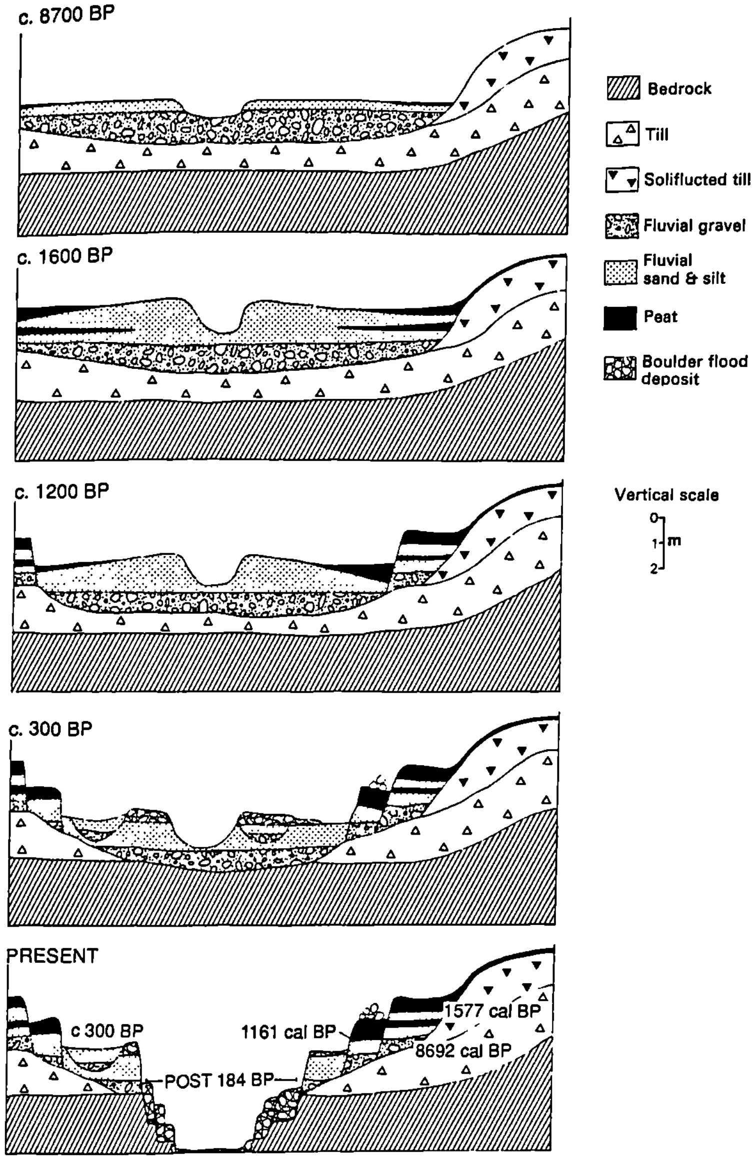


Figure 5.13 Schematic diagram showing Holocene sedimentation history since c.8500 cal BP and valley floor development in Thinhope Burn

very rapid rates (by British standards) of valley floor incision. These changes were initiated in, or shortly after, the late Roman period (c.374 A.D.). Fundamental changes in the erosiveness of flows (stream power) or the erodibility of bed and bank materials (Bull, 1979; Cooke and Reeves, 1976; Schumm et al, 1984) are required for channel entrenchment. Initiation and timing of incision in Thinhope Burn coincides with a number of climate and land-use alterations that may have produced these changes.

The first episode of valley floor entrenchment coincided with climatic deterioration (wetter summers and colder winters) in the fifth and sixth centuries A.D., indicated both by documentary evidence (Lamb, 1977) and raised mire stratigraphy in north (Barber, 1981) and west (Barber and Twigger, 1987) Britain, coming shortly after major woodland clearance in the Northern Pennines in late pre-historic and early historic times (190 B.C. - 250 A.D., Turner, 1979). Valley floor incision would appear to have been triggered by higher flood discharges and stream powers resulting from increased runoff, that was a direct consequence of a wetter climate accentuated, most probably, by vegetation clearance.

The most recent phase of channel and floodplain metamorphosis in Thinhope, which began sometime in the latter part of the seventeenth century, witnessed much more dramatic changes than those that occurred in the late Roman period. It saw the replacement of a relatively stable meandering stream and a floodplain accreting fine-grained sediment by a vertically and laterally unstable low-sinuosity boulder-bed channel with a high coarse sediment load. This transformation appears to have followed widespread entrenchment and extension of the drainage network in the Thinhope catchment. Major erosion of bedrock by the main channel, principally along the valley bottom, together with dissection of boulder-rich till by tributaries on adjacent valley slopes resulted in a significant increase in both the supply and calibre of coarse sediment to the system. A sharp rise in effective precipitation during the later stages of the Little Ice Age (Barber, 1981; Lamb, 1982), shown clearly by documentary evidence of exceptional flooding in north east England (Brand, 1789; Latimer, 1857; Sykes, 1866) and elsewhere in northern Europe (Koutaniemi, 1987) in the late seventeenth and eighteenth centuries, appears to have been the principal cause of channel incision and river transformation. Additionally, intensification of weathering processes during the Little Ice Age probably pre-conditioned streambanks and bedrock to some extent, making them more susceptible to erosion.

Land drainage and agricultural enclosure in the South Tyne valley during the mid and late eighteenth century, as noted by local commentators (Palmer, 1882) also augmented runoff resulting in shorter times to peak flow and greater flood magnitudes. Once channels became entrenched, greater flood depths resulted: higher bed shear stress would have promoted further incision (cf. James, 1991). Rates of incision over the last 200-250 years, however, have varied along the channel, resulting in an uneven pattern of channel degradation, very similar to the development of discontinuous gullies reported by Schumm and his co-workers (Schumm and Hadley, 1957; Schumm et al, 1984). Slope and lithology are important controls on rates of incision: highest rates have occurred in the upper parts of the Thinhope catchment in reaches with relatively high gradients underlain by mechanically weak and fissile shales.

Renewed channel incision in the late 1930s also coincided with a shift to a wetter climate, and intensive gripping (land drainage) in the headwaters of Thinhope, that resulted in a 47 % increase in stream density (Fig. 5.14). One final and important corollary of progressive channel entrenchment is its influence on both the nature and length of the recent alluvial sedimentary record. By limiting the amount of post-flood reworking of valley floor sediment, channel incision has endowed Thinhope with a longer and more complete sequence of flood deposits than would otherwise have been the case given current rates of channel migration. By contrast, the relatively short (c.100 year) coarse sediment flood record in the adjacent Knar Burn catchment (Fig. 5.8) reflects much slower rates of recent channel incision.

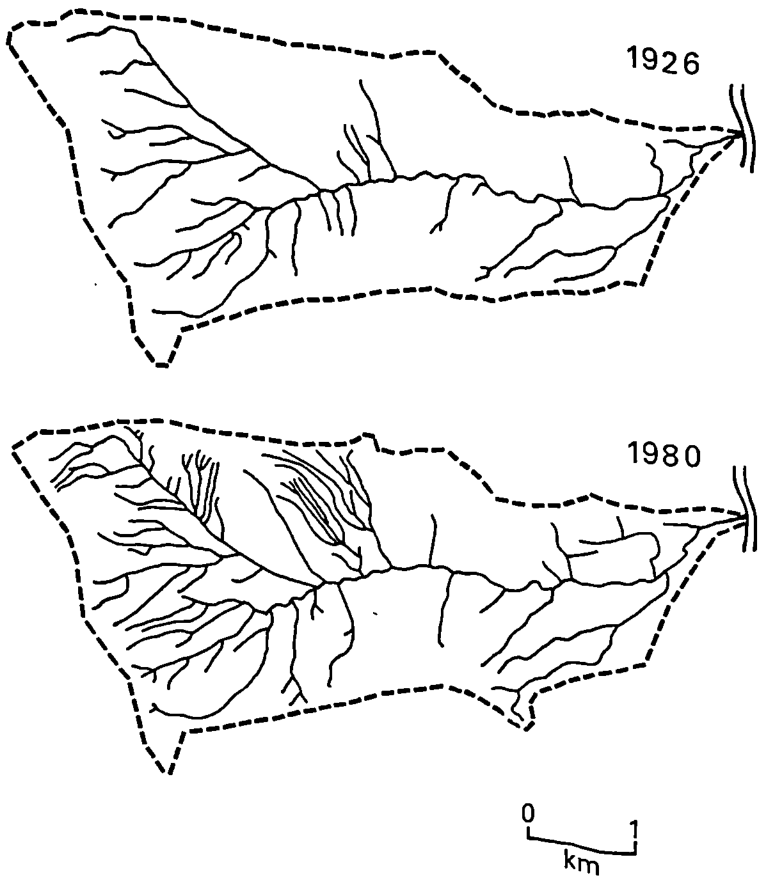


Figure 5.14 Comparison of stream networks in the Thinhope Burn catchment in 1926 and 1980 based on 1:25,000 Ordnance Survey maps

Conclusions

1. The morphological form and sedimentary properties of recent (eighteenth century and later) coarse flood sediments in Thinhope Burn are strongly related to flood water/ sediment ratios that is primarily controlled by sediment supply. Cobble-boulder bars, sheets and splays would appear to have been deposited under Newtonian conditions from flows with relatively low concentrations of sediment. Deposition of boulder berms and lobes in contrast were associated with transitional quasi-Newtonian flows with high sediment loads.

2. In the Thinhope catchment the deposits of 21 large flood events have been identified. Lichenometric analysis shows that all but one of these date from the mid-eighteenth century. Between 1766 and 1960 there is a distinct clustering in the timing of large floods that corresponds with major hydroclimatic trends evident both in northern Britain (Harris, 1985; Lamb, 1977) and north west Europe (Probst, 1989) over this period. Discharge estimates show a decrease in flood magnitude since the late eighteenth century, though a number of large floods occurred between 1929 and 1954. Progressive and continuing confinement of Thinhope Burn within its own alluvium, however, has markedly reduced the availability of coarse sediment and consequently limits the use of largest clast measurements for estimating flow competence and magnitude in more recent (post 1960) flood deposits.

3. The late Holocene (post c.374 A.D.) witnessed a striking transformation of channel and floodplain sedimentation styles in Thinhope. It saw the replacement of a relatively stable meandering channel and a floodplain accreting fine-grained sediment, by a vertically and laterally unstable low-sinuosity boulder-bed stream with a high coarse sediment load. River metamorphosis was associated with major valley floor incision in late Roman times and especially during the eighteenth century. Channel entrenchment during both periods would appear to have been the result of increased runoff and flood magnitude linked to a shift to a wetter

climate, with flow augmented by early historic woodland clearance and drainage of the catchment in more recent times. Thus patterns and rates of valley floor development in the Northern Pennines during the late Holocene (especially in the last 300 years) have been exceptional when viewed in the context of earlier Post-glacial changes. Finally, pronounced incision of many valley floors in the Northern Pennines and elsewhere in upland Britain has generally been considered to have been the product of Pleistocene cold climate processes and meltwater erosion during deglaciation (e.g. Rose and Boardman, 1983). Results from Thinhope Burn, however, demonstrate significant channel incision (up to 8 m) and bedrock erosion in the historical period, and suggests that current models of longer-term Holocene and Pleistocene valley floor development in the British uplands may need to be re-evaluated.

Chapter 6

RESPONSE OF A PIEDMONT REACH OF THE RIVER TYNE TO VARIATIONS IN FLOOD MAGNITUDE AND FREQUENCY, C.1600 - 1990

Introduction

This chapter examines the nature of the sedimentary flood record and river response to flooding in the middle reaches of the River Tyne. A large proportion of the middle Tyne catchment can be classed as piedmont (sensu Newson, 1981) including the middle and lower reaches of the South and North Tyne Rivers and the main Tyne valley as far as Hexham. Recent work has demonstrated that the piedmont reaches of rivers in western and northern Britain have been the most active in terms of planform activity during the last 100 years or so (Hooke and Redmond, 1990), suggesting they are likely to provide a detailed record of river response to flooding over this time period. Furthermore, the intermediate position of the piedmont river zone is important for linking river channel response and flood histories of headwater tributaries and lower reaches of the Tyne.

Although planform development in piedmont rivers has been examined in some detail in Britain (e.g. Hooke, 1977; Lewin, 1976; Macklin, 1986, Richards, 1979), there have been very few studies which have considered the timing and nature of vertical channel response to hydroclimatalogical and land-use changes. This chapter examines the relationship between flooding, sedimentation and the vertical tendency of river channels at Broomhaugh Island, located towards the downstream limit of the piedmont zone. Over the last 200 years or so although there has been limited channel migration in this reach there has been considerable river-bed incision with significant deposition of fine-grained sediment at both overbank and within-channel locations.

Background to the study site

Broomhaugh Island (GR NY 945643, Fig. 6.1) is located in the Tyne valley near Hexham, approximately 3 km downstream of the North and South Tyne confluence. Downstream of Hexham the River Tyne flows through an extensive alluvial basin, c.1 km wide, and Broomhaugh is situated at its western end, with an upstream catchment area of 1918 km^2.

Five historic maps and one A.P. survey have enabled the timing and nature of planform development of Broomhaugh Island since 1769 to be established in some detail (Fig. 6.2). Captain Armstrong's map of Northumberland shows two separate "islands" at Broomhaugh in 1769, while the first edition Ordnance Survey map of 1860 shows only a single island. The dividing channel was therefore cutoff sometime between 1769 and 1860 - most likely in the major flood of 1771 which is recorded as having had a significant impact on the River Tyne in this area (N.R.O.). Since 1860 Broomhaugh Island has been progressively trimmed and streamlined upstream while downstream it has grown through accretion of successive sediment units, in a style similar to that described by Ostercamp and Costa (1987). As a consequence of river-bed incision younger sediment units, wrapped around the downstream edge of the island, form a series of terraces of varying heights.

Sampling strategy and methodology

Survey and levelling of Broomhaugh Island was undertaken to establish the number, location and morphology of alluvial units. The main alluvial features of the island are shown in plan and cross-section in Fig. 6.3, and described briefly below.

1. A central upstanding 'core' at 6 m above the present river bed which narrows downstream, and has a similar height to the lowest Holocene terrace in this reach of the Tyne valley.

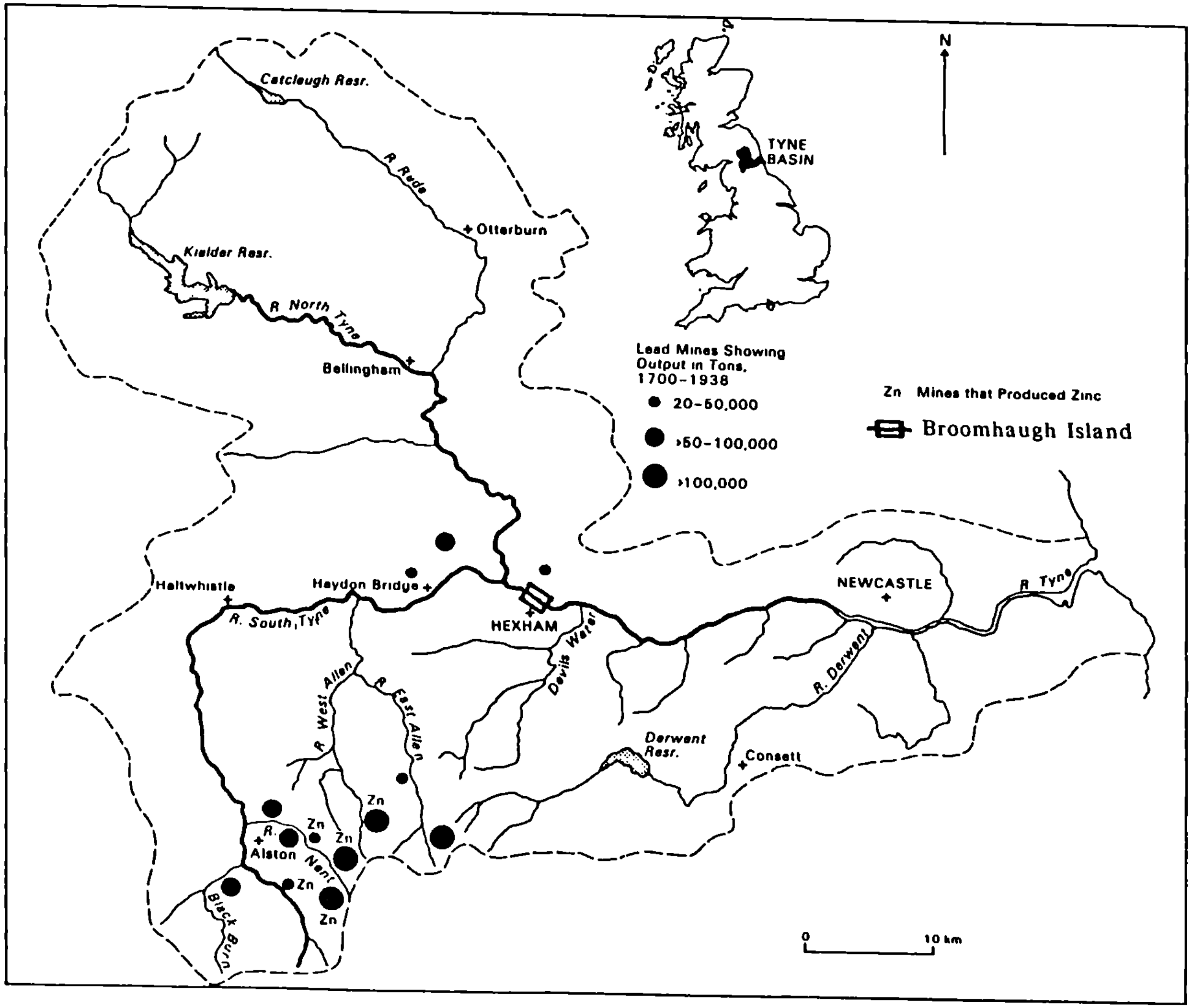
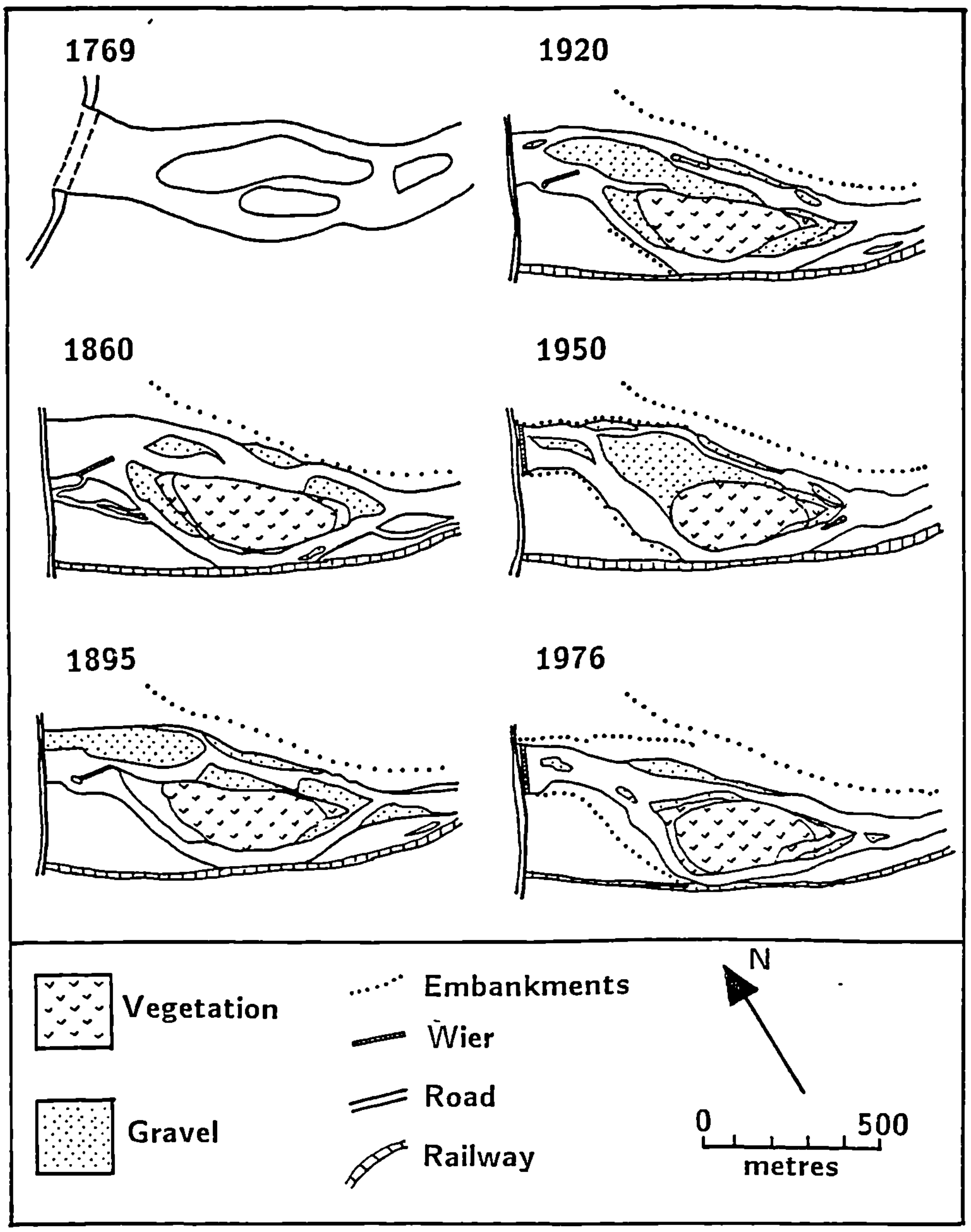


Figure 6.1 Map of the Tyne catchment showing location of Broomhaugh Island



<u>Figure 6.2</u> Maps showing channel change at Broomhaugh Island between 1769 and 1976

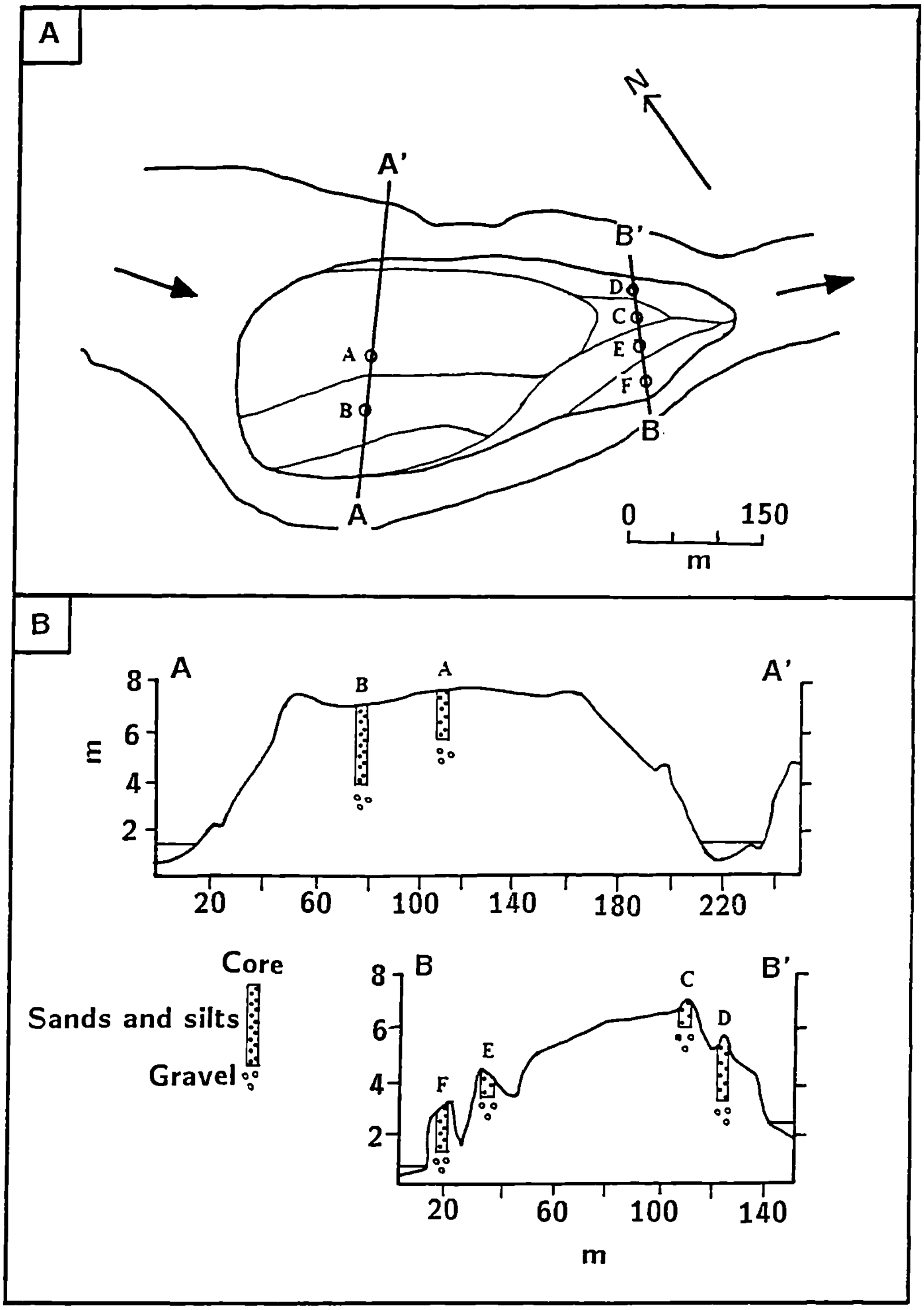


Figure 6.3 (a) Schematic plan of Broomhaugh Island showing location of core/sampling sites and cross-sections (b) Cross-sections showing thickness of fine-sediment and height of alluvial units

2. A linear depression approximately 0.75 m lower following the line of the 1769 channel, 5.25 m above the present river.

3. A series of inset terraces downstream of the central core at levels of 5, 4.5, 4 and 3 m above the present channel bed.

It should be noted that recent (post 1940) incision has largely been concentrated at the lower end of the southern anabranch at Broomhaugh and the channel bed on that side of the island is c.1 m lower than the northern channel. Terraces of similar age therefore lie at different heights above the river bed on opposite sides of the island.

Sediments from every major morphological unit were sampled using a Eijkelkamp 4 cm diameter sand auger. Location of the core sites, six in total, and sediment thickness is shown in Fig. 6.3 (points A - F). Coring at each site was terminated at the sand/gravel contact, and cores ranged in thickness from 0.82 - 2.68 m. The sandy nature of the material rendered transport of whole cores impracticable, therefore sediments were described, sub-sampled (on the basis of stratigraphic units) and bagged in the field.

Sediment organic and heavy metal content were determined following the same procedures used at Low Prudhoe (chapter 4). However, in the light of the limited success of graphical moment statistics in differentiating flood units at Low Prudhoe, and the low levels of silt and clay in Broomhaugh sediments, a visual comparison method was used for determining the <u>modal</u> grain size. A sediment sub-sample was compared with a reference chart graded at 0.5 phi intervals, ranging from very fine sand (4.0ϕ, 0.06 mm) to coarse sand (-1.0ϕ, 2 mm), under a binocular microscope.

Sedimentary characteristics of flood deposits

Alluvial units on Broomhaugh Island consist of generally well-bedded, sands and silty sands with low dips very similar to those studied at Low Prudhoe. Individual flood events were differentiated on the basis of predominantly textural discontinuities and variations in grain size, and all three types of flood deposit identified at Low Prudhoe (Type 1: medium - fine sand, Type 2: fine - very fine sand, Type 3: silty fine - very fine sand) were represented in Broomhaugh alluvial sediments. However, limited colour variation and more subtle grain size changes at the latter site make differentiation of individual flood units more difficult, and estimates of the number of major floods represented in each alluvial unit must be considered a minimum. Sedimentary characteristics and organic content of sediments comprising each core are described below and illustrated in Figs 6.4 to 6.9.

Core A (Fig. 6.4): Most of the core has a low organic content (<5 % L.O.I.); increasing losses in the top 10 cm probably reflect incipient soil development processes and root penetration. Grain-size fines upward from coarse sand at 184 cm to fine sand at 150 cm. There is a coarser, type 1 (medium sand), flood layer between 150 - 140 cm, and above 140 cm there are alternating laminae of type 2 (fine sand) and type 3 (very fine sand) flood units. Overall there are 10 textural reversals in the sequence indicating a minimum of 10 major floods.

Core B (Fig. 6.5): Losses are less than 5 % between 268 and 10 cm, rising to a peak of 18 % in the top 4 cm. Overall grain size fines upward from medium sand at 260 cm to very fine sand at 80 cm depth, though there are a number of smaller scale fining upward sequences superimposed on this trend. Above 80 cm there is less variation in grain size, restricted to alternations between fine and very fine sand and a slight fining upward trend. Larger floods are indicated by coarser type 1 and

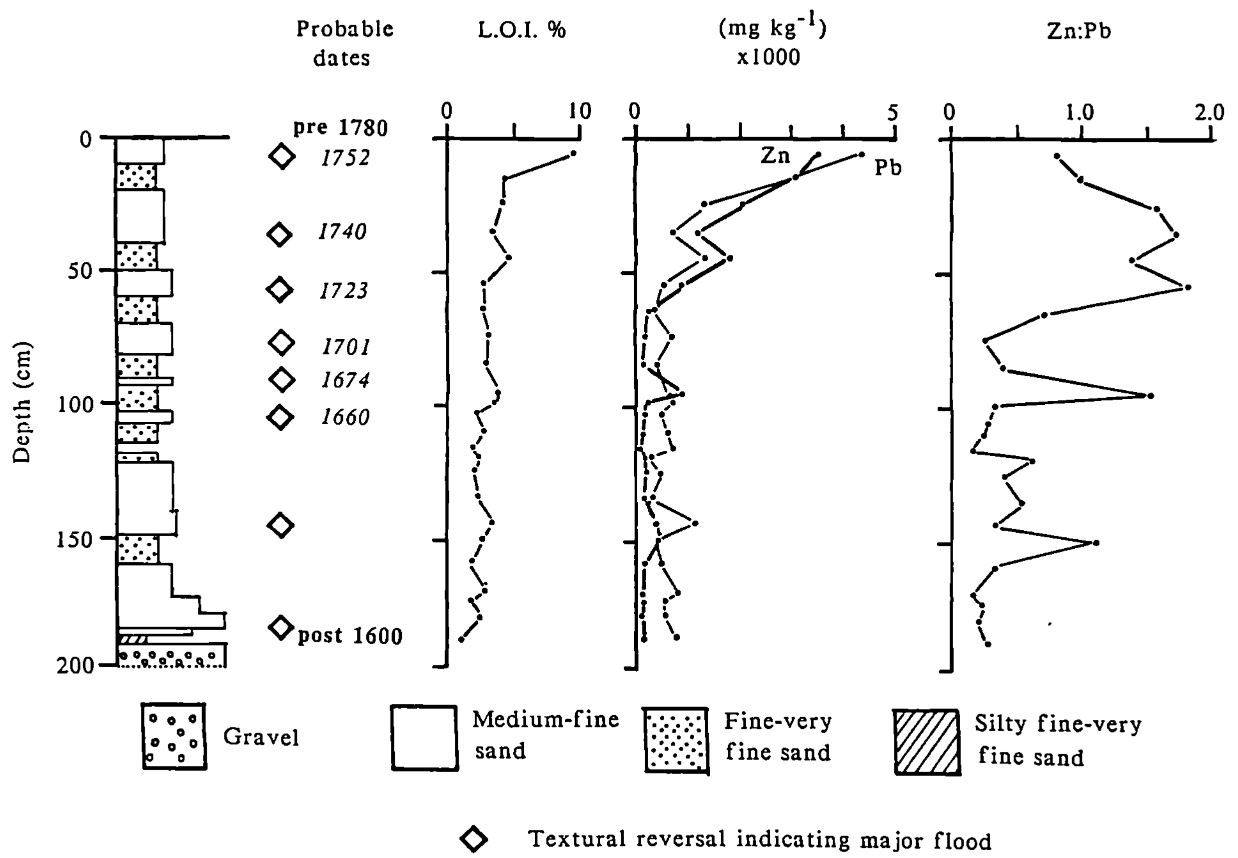


Figure 6.4 Sedimentary log, showing major flood units, organic matter content and heavy metal concentrations of core A. Probable dates are based on heavy metal (italic) and map (bold) evidence

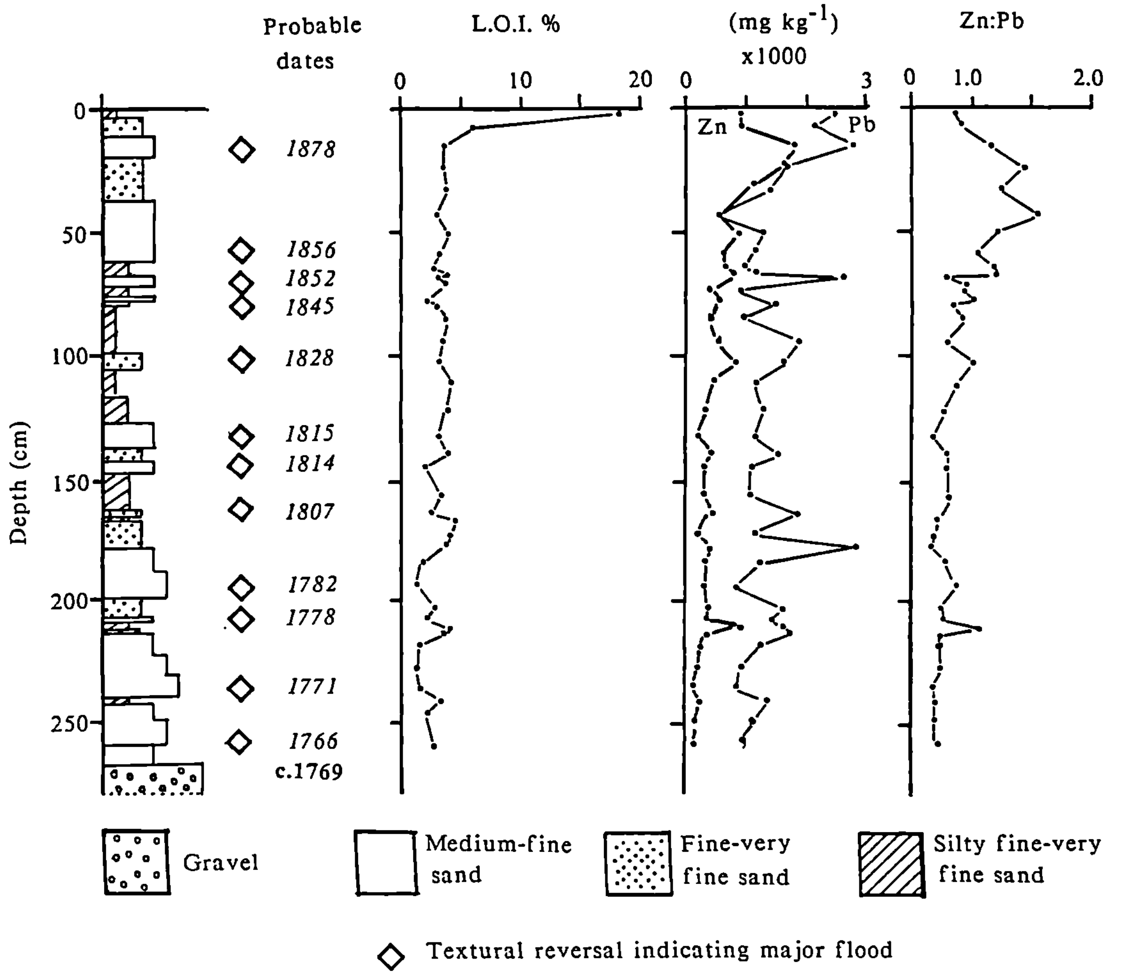


Figure 6.5 Sedimentary log, showing major flood units, organic matter content and heavy metal concentrations of core B. Probable dates are based on heavy metal (italic) and map (bold) evidence

2 layers that form textural reversals at 260, 241, 210, 200, 166, 148, 138, 106, 79, 73, 62 and 20 cm.

Core C (Fig. 6.6): Losses are below 5 % throughout the core and rise in the top 10 cm to 12 %. Grain size is variable although there is an overall fining upward trend from medium to very fine sand. Four major flood (type 1 and 2) units are present at 82, 62, 57 and 20 cm.

Core D (Fig. 6.7): Losses are below 5 % in the lower half of the core, with a small peak between 192 - 184 cm. Above 112 cm losses are generally over 5 %, although the sequence shows no marked rise in L.O.I. towards the surface. The relatively low L.O.I. values in the top of this core (and in E and F, described below) compared to those in cores A, B and C are most likely due to the recent age of the deposits, providing little time for soil development to take place. Grain size changes correspond with the major changes in organic content - finer sediments are associated with higher losses. Between 222 and 112 cm there is a slight coarsening upward trend in grain size and type 1 flood units (medium sand) are predominant in the sequence, with textural reversals at 200, 188, 181, 156, 141 and 130 cm. In contrast above 112 cm type 3 sediments (very fine sand) predominate, and coarser flood laminae (at 100, 91 and 56 cm) form only relatively thin layers (c.2-5cm), with the exception of the top 27 cm which comprises a major flood deposit.

Core E (Fig. 6.8): Losses are around 5 % up to 40 cm depth, above which they rise progressively to a value of 8.5 % at the top of the core. Overall grain size fines upwards from medium to very fine sand interrupted by textural reversals at 90, 61 and 40 cm, indicating 3 major floods.

Core F (Fig. 6.9): Losses range between 5 - 7 % throughout most of the core with peaks of 9 - 10 % at 89 and 76 cm. Between 206 - 86 cm there is a

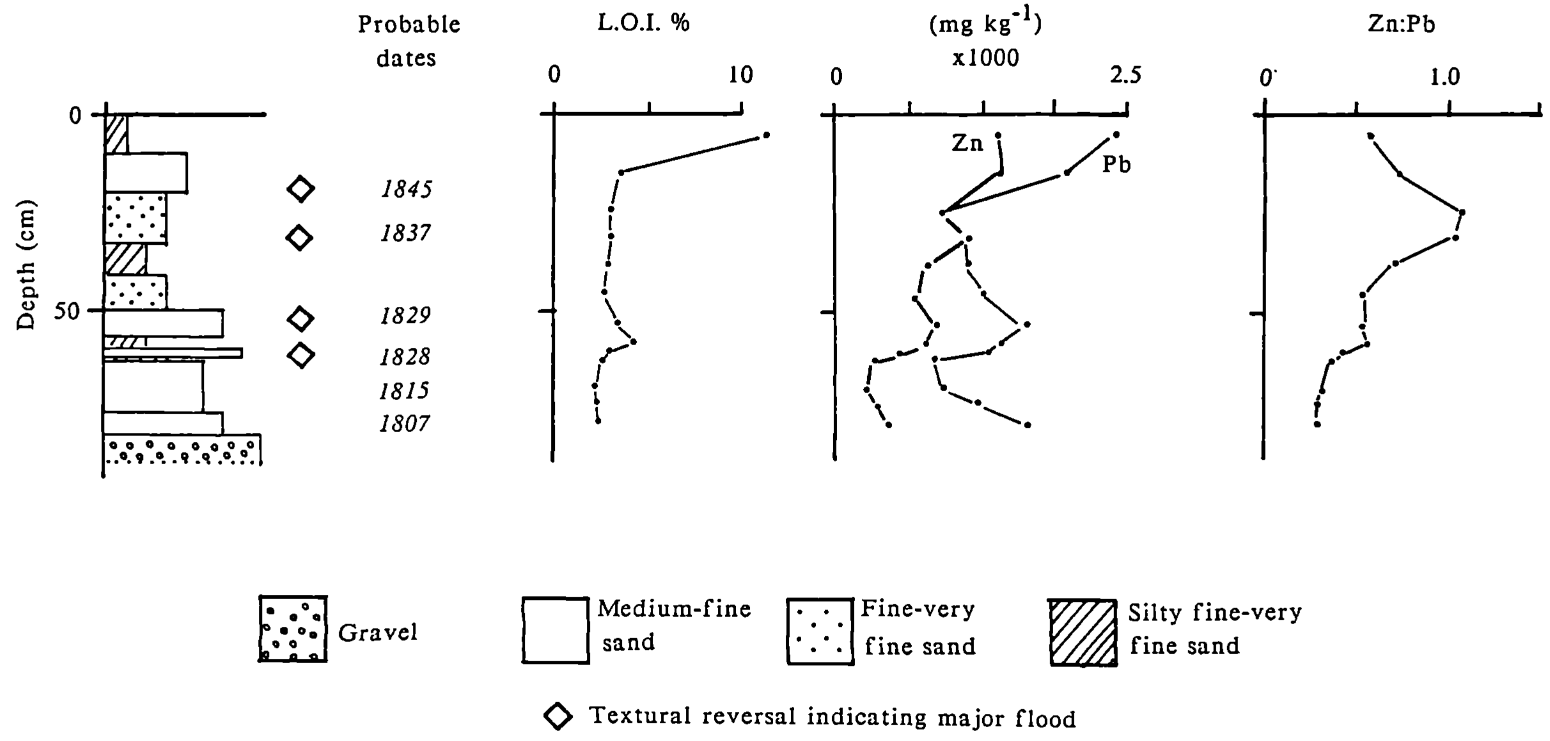


Figure 6.6 Sedimentary log, showing major flood units, organic matter content and heavy metal concentrations of core C. Probable dates are based on heavy metal (italic) and map (bold) evidence

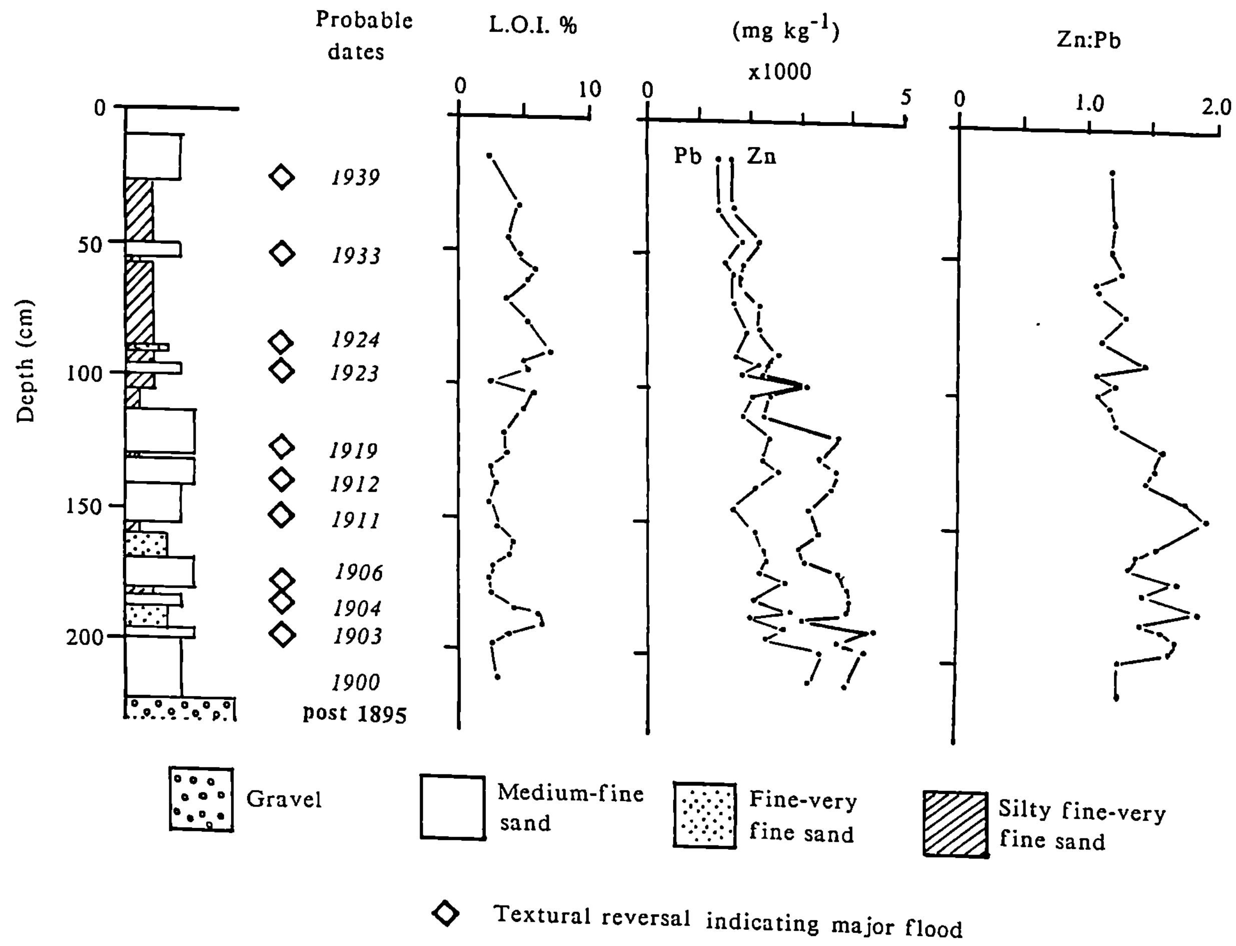


Figure 6.7 Sedimentary log, showing major flood units, organic matter content and heavy metal concentrations of core D. Probable dates are based on heavy metal (italic) and map (bold) evidence

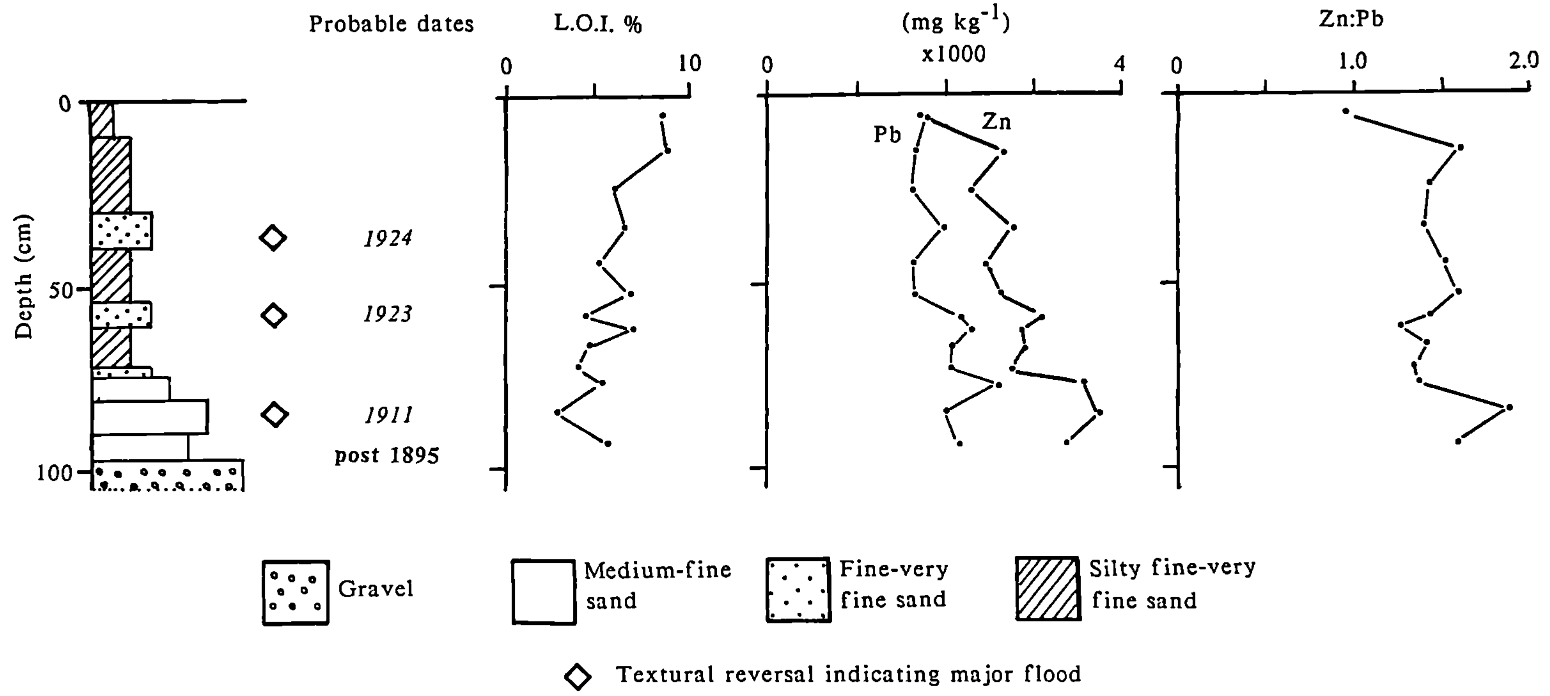


Figure 6.8 Sedimentary log, showing major flood units, organic matter content and heavy metal concentrations of core E. Probable dates are based on heavy metal (italic) and map (bold) evidence

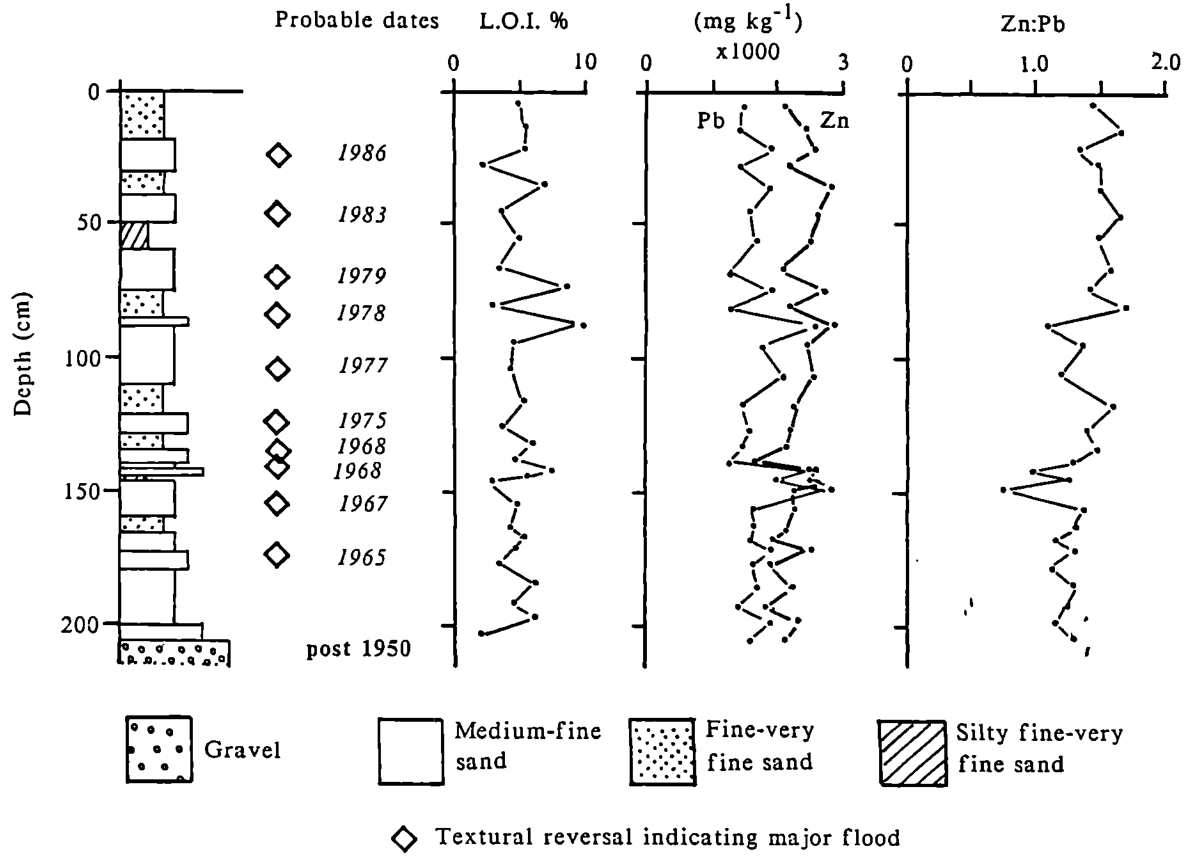


Figure 6.9 Sedimentary log, showing major flood units, organic matter content and heavy metal concentrations of core F. Probable dates are based on heavy metal (italic) and map (bold) evidence

preponderance of type 1 and 2 flood layers of medium and fine sand with textural reversals at 206, 180, 160, 145, 140, 129, 110 and 89 cm. Above 86 cm flood units are generally finer grained, alternating between fine and very fine sand layers containing 3 further textural reversals. At least 11 floods are represented in the overall sequence.

All 6 cores from Broomhaugh Island exhibit overall fining-upward trends in grain-size and systematic upsection changes in the nature of flood layers. Type 1 layers tend to prevail in the lower half of the sequences with an increasing proportion of type 3 layers towards the surface. Loss-on-ignition values are generally higher in cores D, E and F, though cores A, B and C show marked increases in the top 10 - 20 cm, reflecting development of surface vegetation and incipient soil processes.

Age of alluvial units

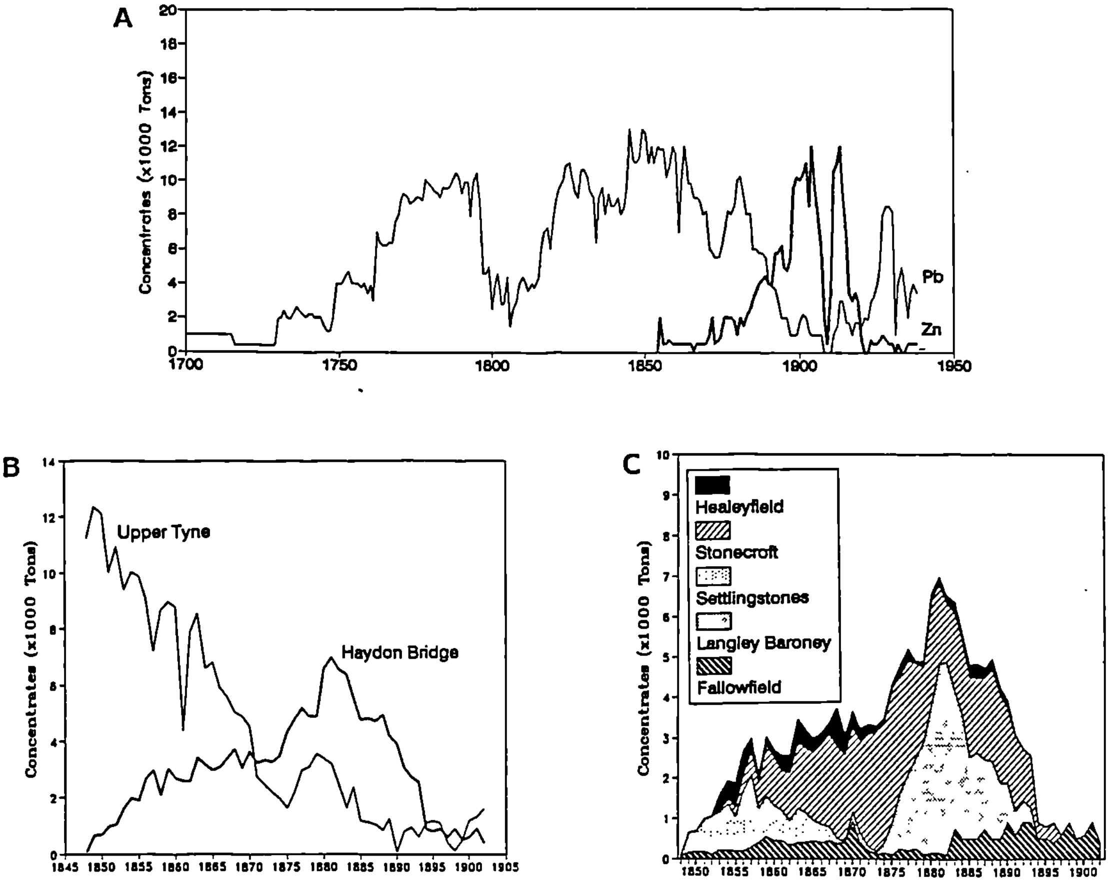
Map and aerial photographic evidence

A maximum age for initiation of fine sediment accretion for alluvial units deposited since 1769 was determined from topographic maps (Figs 6.2, 6.3). Initiation of sedimentation of the central section of Broomhaugh Island (core A) pre-dates 1769. As discussed earlier, dismemberment of the anabranch shown on the 1769 map is likely to have taken place in the 1771 flood and provides a maximum date for core B. Although it is possible that fine-grained sediments were accumulating within the channel prior to cutoff. Accretion of sediments at C occurred after 1769 and before 1860. Indeed, significant fine-grained sedimentation of alluvial units A, B and C had probably largely ceased by the mid nineteenth century as all three sites are represented as well-vegetated areas on the 1860 map. The 1860 map also shows the sites where cores D and E are located as active gravel, indicating that fine sediment accretion had not begun at this stage. The deposits at D and E have essentially the same planform on both the 1895 and 1920 maps indicating that stabilisation had occurred by the end of the nineteenth century with incision of the river bed elevating the gravel surface above the level of low-moderate flows. Sites D and E are shown with patchy vegetation cover on the 1920 map and with complete vegetation cover (grass and scrub) by 1950. They were probably still inundated by flood waters fairly regularly up until 1920 but very rarely by 1950. The lowest terrace (core F) is shown as a partially attached gravel bar on the 1950 map, and as an attached, semi-vegetated unit on the 1976 A.P. Fine sediment accretion at F therefore commenced sometime between these two dates.

Chemostratigraphy

Flood sediments within alluvial units at Broomhaugh were dated using heavy metal concentrations following the same general procedure used at Low Prudhoe. It was anticipated, however, with the proximity of the Haydon Bridge mining area to Broomhaugh Island (Fig. 6.1), that local mining output variations would be preferentially registered over production further upstream. In contrast to Low Prudhoe which is located sufficiently far downstream for a catchment-wide mining record to be fully integrated within recent alluvial sequences. Although production from Haydon Bridge mines generally followed the overall trend of other mines in the Tyne catchment (Fig. 6.10), there were some significant differences. In particular, the most important mines in the Haydon Bridge area were developed after 1850 during a period of decreasing lead production in the Alston Moor area (e.g. the large peak in lead production at Langley Baroney mine between 1873 and 1893, Fig. 6.10).

Additionally, Fallowfield Mine at Acomb (NY 941679), one of the oldest lead mines in the Tyne catchment, is drained by the Red Burn that enters the Tyne on the north side of the valley only c.1 km upstream of Broomhaugh Island. A phase of mining at Fallowfield between 1611 and 1690 (Smith, 1923) occurred prior to significant production elsewhere. It is likely that this mining would be registered at Broomhaugh if flood sediments of that age are present.



<u>Figure 6.10</u> (a) Lead and zinc production in the Tyne catchment 1700-1938 (from Dunham, 1944) (b) Comparison of lead production from Haydon Bridge area mines with production in the rest of the Tyne catchment (c) Lead production figures for individual mines in the Haydon Bridge area (from Smith, 1923)

Although there are no systematic records available for lead and zinc yields since 1938, Dunham (1990) has estimated that this period accounts for only a very small proportion of total production (0.67 % of lead and 11.9 % of zinc). However, a large proportion of zinc production since the second world war resulted from re-working of spoil heaps at Langley Baroney and Stonecroft-Greyside mines in the Haydon Bridge area (during the 1950s). Alluvial sediments deposited at this time are therefore likely to contain relatively high zinc concentrations.

A summary graph of sediment lead and zinc concentrations for each alluvial unit (Fig. 6.11) shows a clear pattern with 3 distinct groupings. Core A has low concentrations of both lead and zinc indicating deposition prior to large scale mining. Cores B and C have low zinc levels and high lead levels characteristic of deposition comtemporaneous with lead mining but before initiation of large scale zinc mining. Cores D and E have the highest zinc concentrations, consistent with deposition during large-scale upstream zinc mining which took place between 1898 and 1920. Core F plots near to, but below, D and E, and has lead and zinc concentrations typical of contemporary (post-mining) vertical accretion sediments (e.g. levels recorded for 1986 overbank deposits, Macklin and Dowsett, 1989). The graph shows that post-mining heavy metal concentrations are much higher than pre-mining background levels. Examination of upsection lead and zinc variations allowed age estimates to be refined and detailed chronostratigraphies to be constructed. The number of prominent flood layers between dated horizons was compared with the documentary flood record for the middle Tyne valley and probable dates assigned to prominent flood layers (Figs 6.4 to 6.9).

Core A (Fig. 6.4): Although lead and zinc values are low (zinc:lead ratios are generally less than 1) they are higher than those obtained for uncontaminated alluvium elsewhere in the catchment (e.g. background/pre-mining levels of 130 mg kg^{-1} lead and 115 mg kg^{-1} zinc at Farnley Haugh (NZ 004633), 6 km downstream of Broomhaugh, Macklin et al, in press). It seems most likely that deposition of the

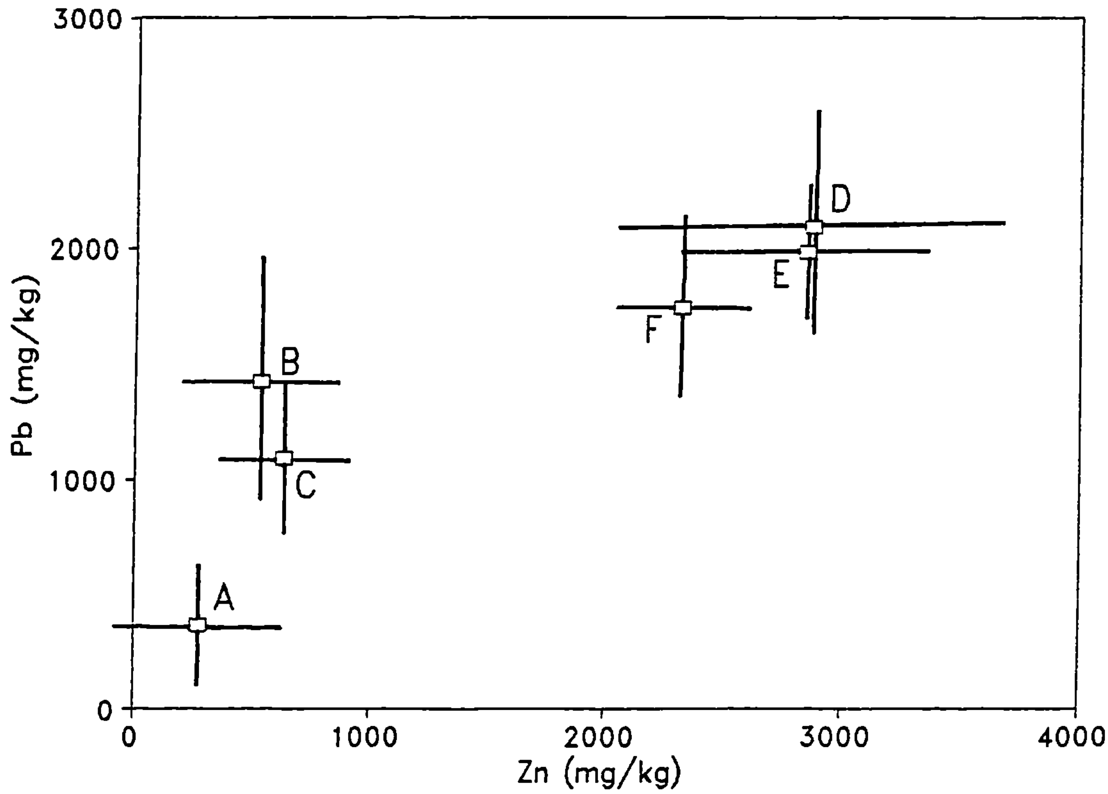


Figure 6.11 Summary heavy metal characteristics of alluvial units at Broomhaugh Island showing mean and standard deviation lead and zinc values

majority of this unit (180 - 50 cm) took place in the seventeenth and early eighteenth centuries during an early period of lead production at Fallowfield Mine. There is however a marked increase in heavy metal concentrations above 50 cm which may in part be due to recent atmospheric fall-out and organic complexing (especially in the top 10 cm of the profile) but more probably represents deposition after the initiation of larger scale lead mining around the mid eighteenth century. Metal based age estimates for major flood units are shown in Fig. 6.4.

Core B (Fig. 6.5): Sediment lead concentrations of between 1000 and 3000 mg kg^{-1} can be matched in detail to lead production figures between 1760 and 1880. The slight rise in zinc levels at 75 cm corresponds to increase in production after 1850, and the extended peak above 20 cm to production in the 1880s. The lead peak above 40 cm, associated with production from the Haydon Bridge mines, confirms these age estimates.

Core C (Fig. 6.6): Variations in sediment lead concentrations in core C correspond to production figures for the period between 1805 and 1850. Relatively low zinc concentrations (< 1000 mg kg^{-1}) indicate that deposition ceased before the 1880s. Thus sedimentation at B and C was roughly synchronous.

Core D (Fig. 6.7): Values of 3000 to >4000 mg kg^{-1} zinc between 220 and 110 cm are believed to be associated with the peak of zinc mining in the Tyne catchment which took place between 1898 and 1920 (Dunham, 1990). The rise in lead levels between 100 and 89 cm probably corresponds with the revival in lead mining after 1922. Above 89 cm lead and zinc concentrations fall progressively, and peaks and troughs mirror each other indicating no preferential mining input. Deposition at this site therefore ceased before war-time production began to re-introduce contaminated material into the river.

Core E (Fig. 6.8): This core has similar *average* sediment metal concentrations to core D (Fig. 6.7), although lower overall zinc levels, and the absence of a basal lead peak, suggest deposition began slightly later. Additionally, the fall-off in metal concentrations in the top half of core E is much less marked than that in D, suggesting that sedimentation ceased earlier.

Core F (Fig. 6.9): Cartographic evidence shows sedimentation at F began sometime after 1950. Sediments deposited at Broomhaugh during the 1950s would be expected to be characterised by high zinc concentrations and high zinc:lead ratios reflecting upstream mining/re-processing of zinc which continued until the end of the decade (Dunham, 1990). Zinc:lead ratios near to 1, therefore, in the bottom 140 cm of core F suggest that accumulation started after 1960. Above 140 cm, although peaks and troughs in lead and zinc concentrations coincide, indicating no preferential mining input, zinc:lead ratios increase. This is most likely the result of the higher relative mobility of zinc compared to lead (Macklin and Dowsett, 1989) and progressive re-working and re-distribution of contaminated sediment from depositional sites upstream.

In summary, heavy metal analysis at Broomhaugh indicates that there have been 4 major periods of sedimentation over the last 400 years. These are dated to between c.1600 - 1740, 1760 - 1880, 1898 -1939 and 1965 - 1990.

Discussion: flood frequency estimates and sedimentation rates

1. Flood frequency

The number of major floods identified in alluvial sediments deposited since the beginning of the seventeenth century at Broomhaugh can be compared to the documentary flood record over the same time period (Fig. 6.12). The sedimentary flood record at Broomhaugh appears to be more closely matched to major documented flood events (shown separately in Fig. 6.12) than to more moderate events. Fig. 6.13 illustrates the main trends in grain-size over time in terms of the relative proportion of flood sediment types deposited, and Table 6.1 summarises average L.O.I., number of major floods, and sedimentation rates on a yearly and per flood basis.

c.1600-1740

During this period there are 8 sedimentary and 4 documented major floods. Documentary flood records, however, are unreliable prior to 1700-50 and generally underestimate the actual number of floods that occurred (Archer, 1987). Type 1 and type 2 flood layers dominate (medium and fine sand) the sedimentary sequence, and accumulation rates are relatively low (1.47 cm a^{-1}). Sedimentation of the central part of Broomhaugh Island, core A, took place before the Tyne had significantly incised (this unit corresponds with the lowest extensive Holocene terrace in the main Tyne valley), and during flood conditions sediment would have been deposited over a wide area of the valley floor resulting in a relatively thin layer of sediment, and low rates of accumulation.

1740-1760

Approximately 1 m of channel-bed incision. The documentary flood record indicates 2 major floods occurred in this period, though this may be an underestimate (see above).

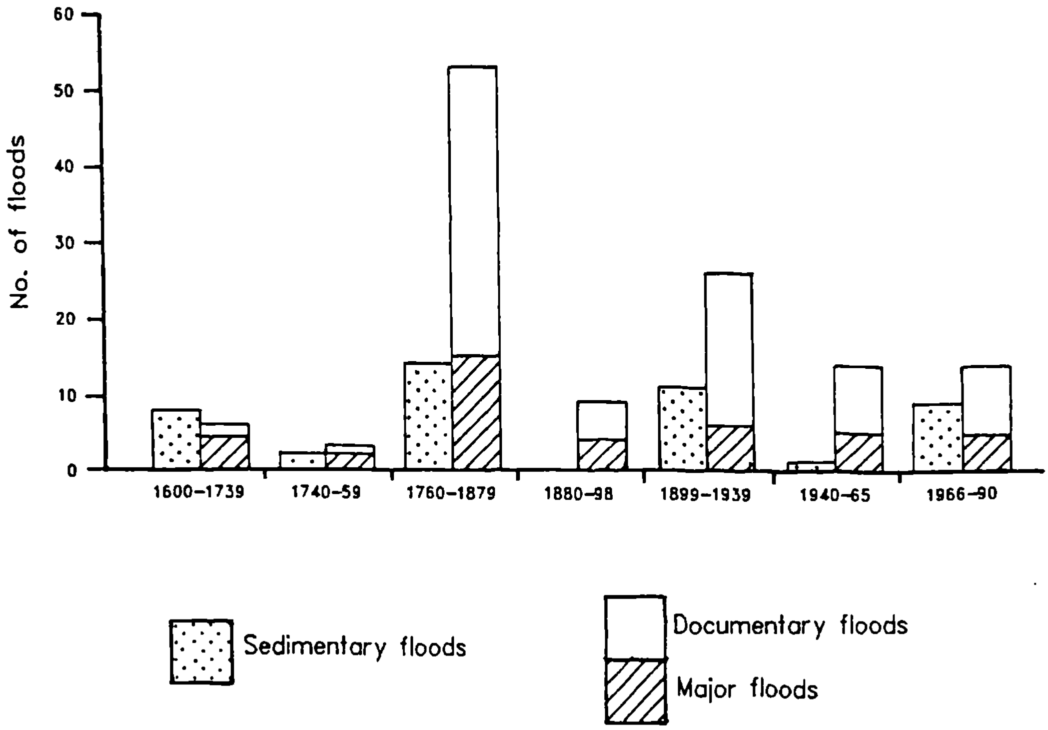


Figure 6.12 Number of documentary and sedimentary floods recorded in dated periods

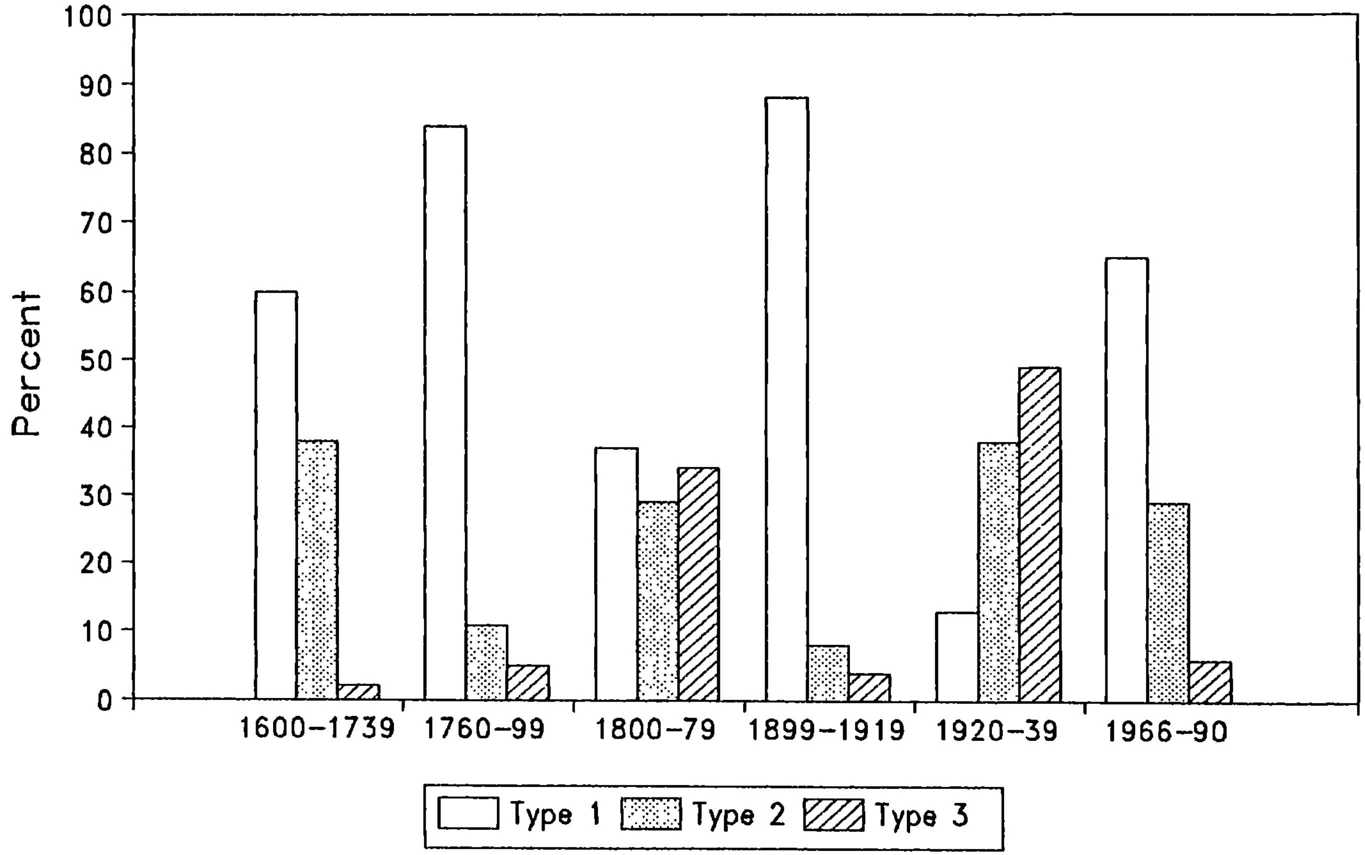


Figure 6.13 Grain-size trends in fine-grained alluvial units at Broomhaugh Island, c.1600-1990

1760 - 1880

Throughout this period sedimentary floods (recorded in cores B and C) are fairly closely matched to major documentary floods. Both records indicate an increase in flood frequency towards the latter part of the nineteenth century with slightly higher sedimentation rates in core B reflecting deposition during the period of increased flooding. Grain-size trends show a decrease in the proportion of coarser (type 1) layers and an increase in finer (type 3) layers over the period, corresponding with progressive increase in relative elevation of the depositional surface above the channel bed.

1880-1898

One metre of channel-bed incision. Nine floods are recorded in the documentary record, including 4 major events.

1898 - 1939

Following channel-bed incision, fine-grained alluvial sedimentation at D and E took place on former channel gravel bars. Up to 1920 the alluvial flood record at Broomhaugh significantly overestimates the number of major floods, indicating that relative elevation of the depositional surfaces was sufficiently low for sedimentation to occur in moderate, as well as more major events. After 1920, however, the trend is reversed with fewer major floods recorded in the sedimentary than documentary record, reflecting progressive censoring of the stratigraphic record with increasing surface elevation. As a consequence, although actual flood frequency increased over the period, the frequency of flooding at Broomhaugh as recorded in alluvial sediments decreased. Grain size changes up profile follow the same general trend as between 1760 and 1880, with a high percentage of type 1 flood layers at the beginning of the period, progressively decreasing over time. Cessation of sedimentation at E by the late 1920s indicates that incision may have been initiated earlier in the southern channel anabranch.

1940 - 1965

A major period of channel-bed incision, with 1.75 m to the north and 3.0 m to the south of Broomhaugh Island. A total of fourteen floods are documented for this period containing 5 major events.

1965 - 1990

Preferential incision of the southern anabranch has resulted in this channel receiving a larger share of runoff (and sediment) than the northern anabranch. Significantly more major floods are recorded in the sedimentary record (core F) and overall grain-size is coarse, with type 1 and 2 layers forming over 90 % of the sequence.

2. Relative elevation of depositional surfaces

A number of previous studies have demonstrated the importance of minor height variations in controlling the nature of floodplain sedimentation (e.g. Knox, 1987; 1989; Nanson and Page, 1983; Taylor and Woodyer, 1978). Differences between sedimentary and documentary estimates of flood frequency at Broomhaugh Island further highlight the control of relative surface elevation on the deposition of fine-grained flood sediment.

Immediately following incision, accretion of fine sediment takes place on low elevation gravel surfaces which can be inundated during moderate as well as more major floods resulting in the deposition of relatively coarse sediment (type 1 flood units). With progressive sedimentation relative height differences increase and a larger proportion of type 2 and 3 flood layers are deposited. The alluvial record shows an apparent decrease in flood frequency as larger flows are required for inundation of the surface, and, as the documentary flood record tends to record only large floods, sedimentary and documentary records converge.

The results of investigations at Broomhaugh have several implications for reconstruction and interpretation of sedimentary palaeoflood records. Most significantly, they show that sedimentary flood frequency estimates reflect relative channel position as well as flood magnitude, and in order to assess changes in flood frequency at a site it is necessary to establish fairly precisely the relative elevation of the depositional surface above channel-bed during the period of sedimentation. In vertically dynamic reaches such as Broomhaugh, it is essential to establish precisely the timing, magnitude and location of river-bed incision (or aggradation).

3. Sedimentation rates

Notwithstanding variations in sedimentation rates between synchronous alluvial units (brought about by differential relative elevation) rates of accumulation of alluvial sediments on Broomhaugh Island have increased by a factor of 6 over the last 300 years from 1.47 cm a^{-1} in the seventeenth century to 8.28 cm a^{-1} since 1955 (Table 6.1). River bed incision over this period has lead to progressive channel confinement with floods that would have inundated a large area of the floodplain, now restricted within the channel. Hence, given the same sediment load greater depths of sediment are deposited in individual floods. In detail, variations in sedimentation rates occur in response to variations in sediment supply and flood frequency and magnitude. In particular, high rates of vertical accretion in the 1920s (8.33 cm a^{-1}, unit E, Table 6.1) appear to be related to enhanced supply of fine-grained sediment from a series of "sedimentation zones" in the South Tyne valley which experienced high rates of lateral re-working and re-distribution of sediment during that period (Macklin and Lewin, 1989). A marked reduction in riparian vegetation at the South Tyne sites, associated with the release of toxic sediments during zinc mining, is believed to have decreased bank cohesion and resistance to erosion and de-stabilised floodplain and channel sediments (Macklin and Smith, 1990).

Dates of Deposition	Core	Average L.O.I. %	Sedimentation Rate $(cm.a^{-1})$	(cm.flood)
1600-1740	A	2.89	1.47	23.7
1760-1799	B	2.77	1.80	22.0
1805-1850	C	3.69	1.82	22.5
1800-1880	B	3.89	2.25	20.5
1898-1919	E	3.53	5.24	18.3
1910-1919	D	4.68	5.75	23.0
1920-1929	D	6.22	8.33	37.5
1920-1939	E	4.64	5.37	25.5
1965-1990	F	5.15	8.28	20.7

Table 6.1 Sedimentation rates and average loss-on-ignition values for dated periods in cores A - F, Broomhaugh Island

4. Loss-on-ignition

It can be seen from Table 6.1 that average L.O.I. values have increased significantly since the seventeenth century. This is believed to reflect the influx of carbon-rich material associated with coal mining operations in the Tyne Basin (including Acomb, immediately upstream of Broomhaugh Island) which peaked in the first half of the twentieth century. The highest mean L.O.I. (6.22 %) is recorded in sediments dating to the period 1920 - 1929 (unit D). Alluvial units deposited since the decline of coal mining have slightly lower values (5.15 % in core F).

Timing, magnitude and nature of river response to floods at Broomhaugh Island, c.1600-1990

The timing of incision and sedimentation at Broomhaugh Island since the early seventeenth century has been reconstructed in some detail using map evidence and chemostratigraphic analysis. Fig. 6.14 shows the thickness and height of alluvial units. Given differential rates of recent incision in the northern and southern channel branches, heights in Fig. 6.2 are relative to the highest terrace (top of core A). The episodic nature of fluvial processes in this reach is clear with short periods of river-bed incision (c.10 - 30 years) alternating with longer periods of vertical stability and sedimentation (c. 30 - 130 years).

A relatively detailed record of hydroclimatic conditions in the Tyne Basin is available over the last 300 years. This is based on systematic precipitation records (since 1850), documentary flood evidence and proxy hydrological data from raised mires in northern England (e.g. recurrence surfaces at Bolton Fell Moss, Cumbria (Barber, 1981)). These provide an excellent basis for examining the relationship between river behaviour and changes in hydroclimate.

Annual precipitation and flood frequency estimates for the Tyne Basin show decadal-scale variations, with 5 periods of above average annual precipitation and increased flood frequency since the mid eighteenth century (see chapter 3). These occurred in 1760-85, 1824-42, 1878-92, 1923-1939, 1954-1967.

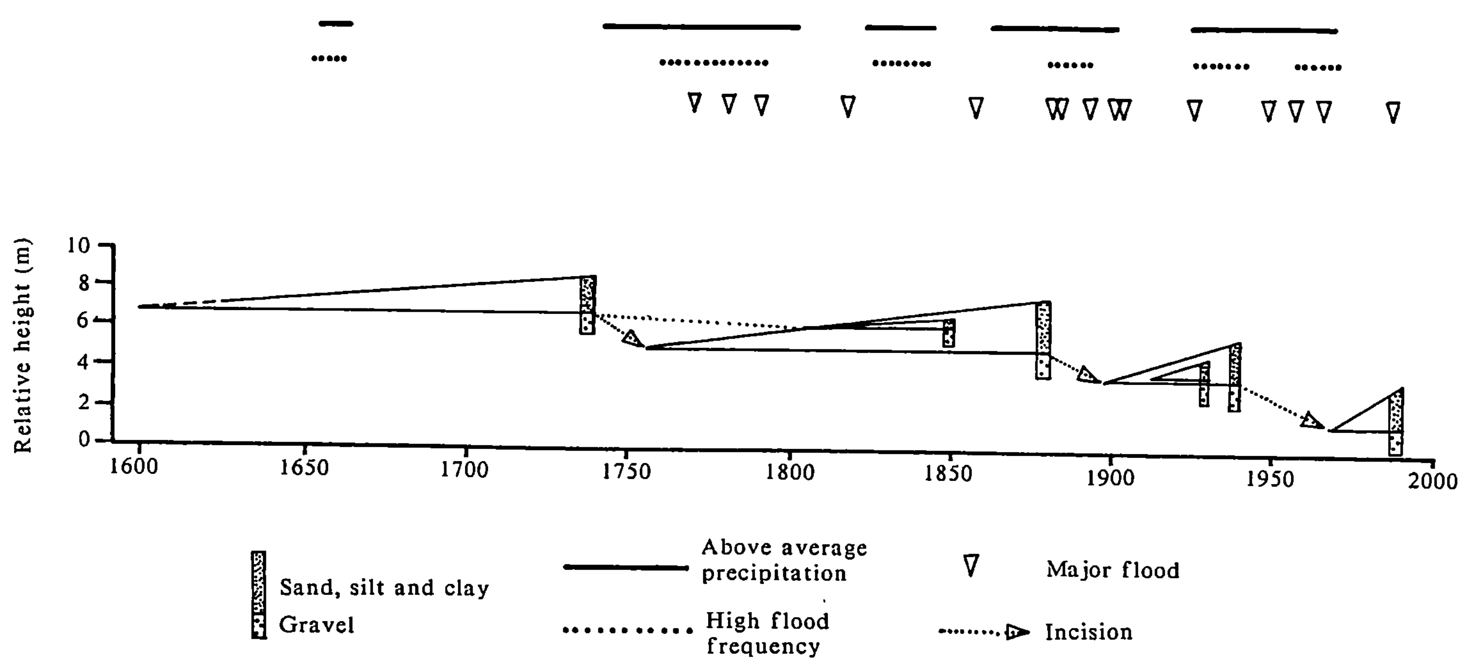


Figure 6.14 Time-level diagram for alluvial units at Broomhaugh Island. Periods of above average annual precipitation and increased flood frequency in the Tyne catchment are also shown

River response

All 3 phases of channel trenching evident at Broomhaugh occurred during periods of above average annual precipitation and increased frequency of high magnitude floods (mid-eighteenth century, 1878-92, 1954-1967). Two further periods of above average annual precipitation and increased frequency of moderate rather than high magnitude floods (1824-42, 1923-1939), however, were characterised by vertical accretion of fine-grained sediments within the bankfull channel, as were the intervening periods with below average precipitation and lower flood frequency.

River bed incision at Broomhaugh therefore appears to be a response to exceptional floods, allowing larger flows to be accommodated within the channel. Clustering of exceptional floods over decadal timescales restricts post-flood recovery and allows the enlarged channel to be maintained. Periods with reduced frequency of large floods allow channel recovery to take place. Moderate floods appear to be important for reworking and redistribution of sediment and channel infilling. Channel recovery (vertical accretion) rates at Broomhaugh were particularly impressive during the 1920s (Table 6.1), reflecting the frequent occurrence of moderate floods, and also high rates of sediment supply.

The magnitude of incision at Broomhaugh Island has increased progressively since the mid eighteenth century both in terms of depth of erosion and total volume of sediment removed (Table 6.2). While accumulation rates of fine-grained alluvium at Broomhaugh have been extremely high, the total volume of sediment deposited since 1760 (Table 6.3) is relatively small and only compensates for around 30 % of that removed. Hence, at present, bankfull channel capacity is around 70 % larger than in the mid eighteenth century.

Rates of removal of coarse sediment from the Broomhaugh reach have also increased in magnitude (by a factor of 3) since the mid eighteenth century (Table

	Total Volume of Sediment Removed		Transport Rate
	($m^3.km^{-1}$)	($tonnes.km^{-1}$)	($m^3.km^{-1}.a^{-1}$)
1740-1770	125,687	335,249	4,190
1880-1898	156,069	416,288	8,670
1940-1965	305,254	814,210	12,210

Table 6.2 Total volume and transport rate of sediment removed at Broomhaugh during successive phases of incision

	Total Volume of Sediment Deposited ($m^3.km^{-1}$)	(tonnes.km)
1600-1740	143,698	229,917
1760-1880	84,788	135,661
1898-1939	43,794	70,070
1965-1990	15,382	65,648

Table 6.3 Total volume of vertically-accreted fine-sediment deposited at Broomhaugh

6.2). Consideration of the downvalley dispersal of eroded sediment suggests extended transport step-lengths. The first significant area of gravel sedimentation below Broomhaugh Island is at Corbridge Bridge (NY 989641), 8 km downstream. Historical map evidence indicates that there has been only limited storage of material within the intervening channel, thus a large proportion of the coarse sediment eroded from the channel bed at Broomhaugh must have been conveyed directly/rapidly through. It appears, therefore, that the high shear stresses generated by large in-channel flows during floods not only intensify river-bed erosion (as has occurred in Thinhope), but also increase the efficiency of the channel to convey sediment. Given this, the long-term preservation potential of fine-grained within-channel sediments at Broomhaugh (and the flood record contained by them) is probably fairly limited. It seems likely that the material will eventually be stripped out, as documented for similar deposits in several rivers in New South Wales, Australia (Nanson, 1986).

Impact of land-use and channel modification

The mid eighteenth century was a period of major change in fluvial behaviour throughout the Tyne Basin, with widespread erosion and channel instability (Macklin, Passmore and Rumsby, in press). Anthropogenic land-use changes at this time appear to have increased river responsiveness to climatic change. Extensive land drainage and agricultural improvement in upland areas and in the main Tyne valley during the eighteenth century considerably enhanced the efficiency of the drainage network so that time to flood peak was decreased and flood magnitude increased (Palmer, 1882).

The construction of flood protection embankments immediately upstream of Broomhaugh Island between 1898 and 1940 may also have accentuated the most recent phase of incision by increasing river bank stability, resistance to lateral erosion and effective channel capacity.

Conclusions

Alluvial sediments at Broomhaugh Island provide an excellent record of river response to climatically determined changes in flood frequency over the last 400 - 350 years. Hence they provide a record of flood "effectiveness". Periods of above average annual precipitation and increased frequency of exceptional floods would appear to result in widespread channel trenching while periods with more moderately-sized floods are associated with lateral re-working and floodplain re-building. Anthropogenic land-use changes in the Tyne Basin during the mid eighteenth century increased the sensitivity of the river to hydroclimatic variations, and the alluvial sequence at Broomhaugh Island provides a detailed record of river response to decadal-scale climatic changes since c.1750.

Chapter 7

OVERVIEW: CHANNEL AND FLOODPLAIN RESPONSE TO FLOOD FREQUENCY AND MAGNITUDE VARIATIONS IN THE TYNE BASIN SINCE C.1600 A.D.

Introduction

The review of literature (chapter 2) highlighted a major priority area for future research in fluvial geomorphology: the relationship between flood frequency and magnitude, channel and floodplain adjustment and the causal mechanisms governing fluvial behaviour, especially the roles and relative importance of climate and land-use, over timescales of 10^1 - 10^3 years. Understanding of these relationships, at a river-basin scale, is fundamental for interpretation of Holocene alluvial sequences and assessment of the likely impact of future environmental changes on river systems. The influence of small to medium-scale variations in hydroclimate is particularly important, given climate changes predicted as a result of global warming over the next 40 years (Macklin et al, in press).

Detailed and temporally well-defined records of river response to flood frequency and magnitude changes in the Tyne catchment since c.1600 A.D. have been reconstructed in chapters 4, 5 and 6, in a range of alluvial settings. The timescale of the study, the last 300 - 400 years, encompasses the latter stages of the Little Ice Age climatic deterioration and subsequent warming phase, and is therefore particularly appropriate in terms of providing a possible analogue for river response to future climate changes (cf. Newson and Lewin, 1991). In this chapter the morphological and stratigraphic records of Thinhope Burn, Broomhaugh Island and Low Prudhoe are compared and integrated in order to critically examine basin-wide linkages between hydroclimate, flooding and fluvial behaviour.

Climate, land-use changes and channel and floodplain adjustment at upland, piedmont and lowland locations, 1600-1990

Fig. 7.1 shows the height, number and thickness of dated alluvial units at Thinhope, Broomhaugh and Low Prudhoe as well as the timing and depth of river bed incision since c.1600 A.D.. Hydroclimate (precipitation and temperature and their extremes), flood frequency and magnitude and land-use variations in the Tyne basin over the last 400 years, also shown in Fig. 7.1, are based on the following information:

i) Hydroclimate. Temperature and precipitation graphs are based on instrumental records for north east England over the last c.150 years (see chapter 3), and proxy data for the preceding period. Proxy information includes an index of wetness derived from recurrence surfaces in Bolton Fell Moss, Cumbria (Barber, 1981). Changes in peat humification are though to reflect increased surface wetness as controlled by changes in precipitation: evaporation ratio. Documentary evidence of climatic conditions in northern England is provided by a number of diarists (e.g. Brand, 1789; Sykes, 1866), and more general information covering England and Wales by Lamb (1977, and sources therein).

ii) Flood frequency and magnitude trends. Based on River Tyne gauging station records for the period since 1960 (Fig. 3.7), and documentary (Fig. 3.8, Appendix I) and sedimentary (chapters 4, 5 and 6) flood histories between 1600 and 1990.

iii) Anthropogenic land-use and channel modifications. Land-use changes in the Tyne catchment over the last several hundred years were discussed in detail in chapter 3, and more detailed site-specific factors in the relevant chapters (chapters 4, 5 and 6).

Fig. 7.1 illustrates the episodic nature of fluvial activity in the Tyne catchment over the last 400 years; decadal-scale fluctuations in channel vertical tendency and alluvial behaviour can be identified at each of the study sites. The

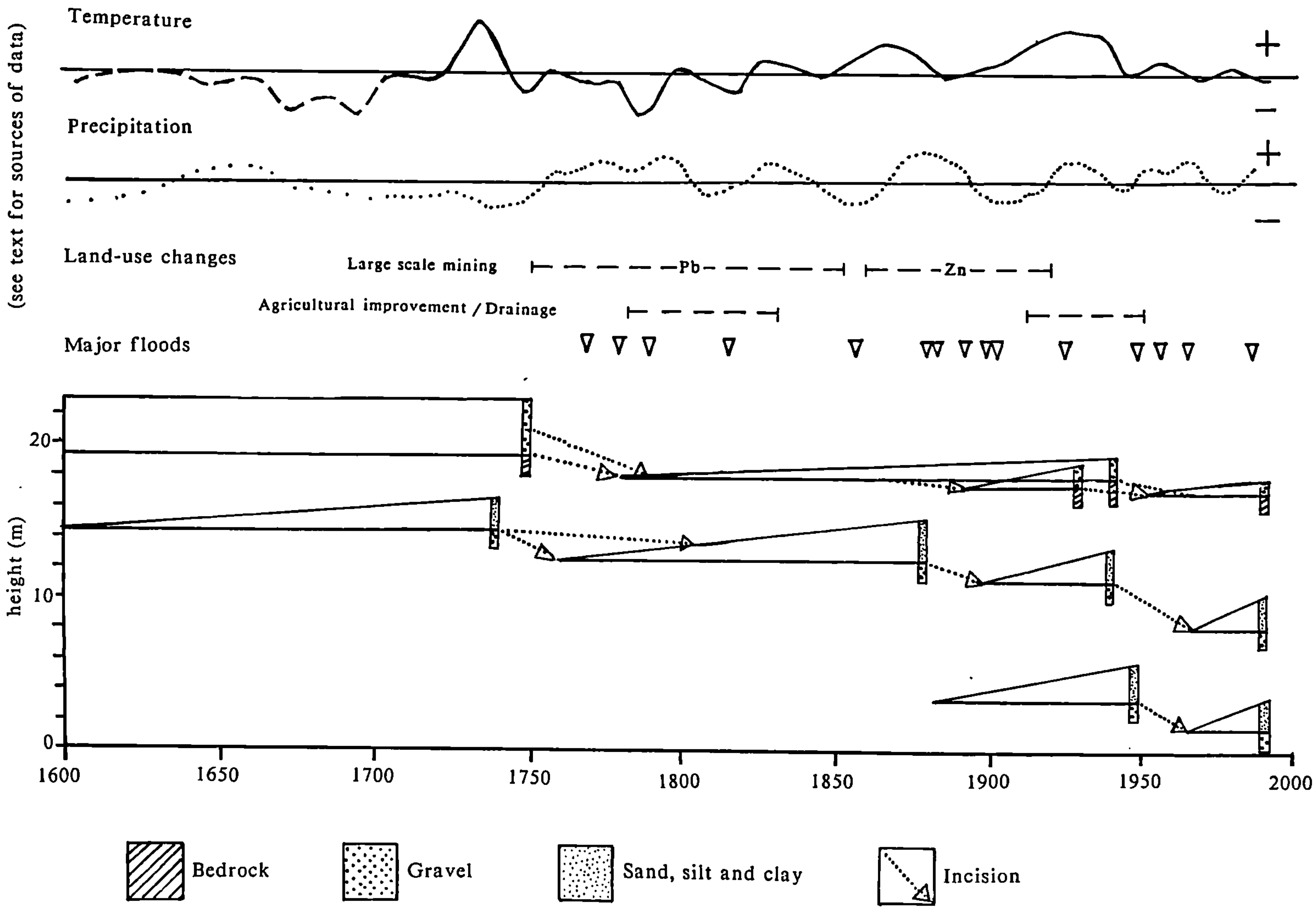


Figure 7.1 Time-level diagram for alluvial units at Thinhope Burn, Broomhaugh Island and Low Prudhoe, 1600-1990. The main trends in flooding, climate (precipitation and temperature) and land-use are also shown

major secular trends in river response are outlined below, along with prevailing hydroclimate and land-use.

1600-1740

Documentary and proxy evidence suggests that the seventeenth century was a period of very low temperatures, corresponding with the severest part of the Little Ice Age, and possibly the coldest century in the last 1000 years (Lamb, 1982). Amelioration began around 1690 and temperatures continued to rise progressively through the first part of the eighteenth century. While the Bolton Fell Moss raised mire sequence indicates relatively high surface wetness for the period 1600 - 1740 (Barber, 1981), a range of other sources suggest only low or moderate annual precipitation amounts (Lamb, 1977) and, notwithstanding the paucity of documentary evidence before 1700, records indicate low frequency of flooding. Low rates of evapotranspiration associated with cool temperatures, and a large proportion of precipitation falling as snow, are likely to have enhanced effective surface moisture levels even though runoff totals were not particularly significant. There was some forest clearance in the Upper South Tyne during this period associated with lead mining operations, which began to take off during the seventeenth century.

This appears to have been a period of generally low rates of alluvial activity in the Tyne catchment. There may have been some small-scale river bed incision in headwater tributaries, the channel cutoff in Thinhope began to infill c.300 B.P.. Broomhaugh Island and other middle and lower reaches of the Tyne (e.g. Farnley Haughs, Macklin et al, in press) were characterised by river bed stability and vertical accretion of fine-grained sediment at floodplain locations.

1740-1790

Several consecutive severe winters around 1740, marked the beginning of a general deterioration of climate lasting for 50 years, characterised by large year to year variation in temperature and precipitation, especially towards the latter part of the period (Lamb, 1977). All proxy sources indicate very wet conditions with high annual precipitation totals and severe flooding. Several important land-use alterations date to this period. Large-scale lead mining began in tributaries of the upper South Tyne and in the lower South Tyne valley around 1750 (Smith, 1923). While mining operations had little direct impact on coarse sediment production, except very locally (Macklin, 1986), they had a more significant impact on suspended sediment yields through direct input of fine-grained mining waste. In addition, deposition of contaminated sediment is likely to have inhibited riparian vegetation growth and colonisation of flood sediments. Progressive agricultural improvement and land-drainage over the latter half of the eighteenth century was associated with cultivation of new land in the South Tyne valley to support the metal-mining workforce (Hunt, 1984). The main effect of land drainage would be to speed up runoff and enhance flood magnitude (cf. Higgs, 1987a).

This was a period of widespread channel trenching and transformation in the upper Tyne catchment, with impressive rates of bedrock incision in Thinhope, and deposition of coarse grained flood deposits. Bedrock erodibility may have been enhanced as a consequence of the prevailing cold conditions: fine-grained, moderately permeable rocks, such as the shales/slates of Thinhope, are particularly susceptible to frost action (Leopold, Wolman and Miller, 1964). Although valley sides in the Thinhope catchment were affected by land improvement operations, the main phase of drainage post-dates initiation of incison and hence was not a causal factor. There appears to have been a less dramatic response in middle and lower reaches of the catchment. At Broomhaugh river bed incision was less marked, and appears to have started later, than in Thinhope and cutoff of the central channel anabranch took place after 1769. Although the Low Prudhoe record is incomplete for this period, an episode of channel incision dating to the late eighteenth century has been documented at nearby Farnley Haughs (NZ 004633, Macklin et al, in press), suggesting entrenchment was fairly ubiquitous.

1790-1860

There was a gradual rise in summer and winter temperatures over this period. Annual precipitation totals appear to have been generally lower than in the preceding period, although there was an episode of enhanced rainfall and increased frequency of moderate-sized floods between 1820 and 1840. Land enclosure and improvement continued throughout the early eighteenth century, but tailed off with the. A period of reduced lead-mining production between 1790 and 1820 was followed by a prolonged peak lasting until 1860 and a rapid decline thereafter (Dunham, 1990).

All three locations seem to have been characterised by vertical channel stability in this period. Moderate flooding in the 1820s and 1830s was associated with lateral reworking and aggradation of coarse sediment in Thinhope (and other headwater tributaries, e.g. Whitewalls), and accretion of fine-grained sediment at Broomhaugh and, probably, Low Prudhoe. This appears to have been largely a time of redistribution and downstream transfer of sediment eroded in the late eighteenth century.

1860-1899

Temperatures, although higher, were still below present levels. Instrumental precipitation records show high rainfall totals, particularly in the 1870s and 1880s, corresponding with increased frequency of major floods. Although there was a marked decline in lead mining in the upper South Tyne after 1860, large-scale production continued in the Haydon Bridge area until c.1890. Additionally there was a a progressive increase in zinc production over the period. No major agricultural land-use changes are recorded.

This period was characterised by channel trenching, beginning around 1860 in Thinhope, and probably later downstream. Incision continued until end of the century in Thinhope and at Broomhaugh, but had probably ceased by 1880-90 at Low Prudhoe.

1900-1940

The long-term warming trend since the end of the eighteenth century continued until the late 1930s, with temperatures peaking around 1940 in northern England (Harris, 1985). Higher rates of evapotranspiration, associated with the warmer conditions, make it likely that smaller amounts of runoff and lower discharge floods occurred for a given magnitude of precipitation event compared to the previous century. Very high annual precipitation totals recorded for the 1920s appear to have been associated with a high frequency of predominantly moderately sized floods. Several important land-use changes occurred during this period. Widespread gripping of upland valley sides (associated with increased agricultural production during the first world war) greatly increased drainage densities in headwater catchments (e.g. Thinhope, Fig. 5.14), and is likely to have accelerated runoff and accentuated flood peaks downstream. Flood embankments and bank protection structures were emplaced on an *ad hoc* basis in middle and lower reaches of the Tyne in the first half of the twentieth century. These would have effectively reduced floodplain inundation and increase the magnitude of in-channel flows. Output from zinc mines peaked between 1900 and 1915, but declined rapidly by 1920. Deposition of zinc-rich mining waste in riparian zones may have promoted bank collapse, but is unlikely to have effected river bed stability.

Low rates of fluvial activity prevailed in the first two decades of the century with channel bed stability and relatively low rates of alluvial sedimentation recorded at Thinhope, Broomhaugh and Low Prudhoe. The 1920s and 1930s, however, were characterised by high rates of fluvial activity and significant transfer of sediment. Rapid vertical accretion of fine-grained sediments within the entrenched channel took place at Broomhaugh and Low Prudhoe, indicating high rates of sediment supply. Aggradation of coarse flood deposits in Thinhope, Whitewalls and Knar Burns appears to have been associated with enhanced rates of lateral reworking and destabilisation of valley-sides, the increase in boulder-size recorded in flood deposits in Thinhope reflecting the input of fresh coarse sediment.

1940-1965

There was a significant cooling trend in annual mean temperature through the 1950s, lasting until c.1965 (Harris, 1985). High annual precipitation totals were recorded in the late 1940s and between 1955 and 1965, associated with increased frequency of high magnitude floods. During the second world war there was a phase of more intensive agricultural land-use. Also lead mining was revived on a small scale and there was some reprocessing of zinc-rich spoil heaps, the latter continuing through to the 1950s. Flood embankments were emplaced at many locations in the middle and lower Tyne following particularly severe floods in 1947 and 1955, and may have enhanced subsequent incision at these locations. Alluvial gravel extraction took place at various locations in the catchment over this period. Gravel extraction has been shown elsewhere to have a relatively localised impact on river channels (e.g. Lewin et al, 1988), and although gravel extraction immediately upstream of Ovingham Bridge in the 1950s and 1960s is likely to have accentuated incision at Low Prudhoe, none of the other study sites was directly effected.

Channel trenching took place in all parts of the catchment, with particularly high rates of incision at Broomhaugh. Initiation of trenching appears to have been diachronous, dating to the 1930s in Thinhope, 1940 at Broomhaugh and 1950 at Low Prudhoe.

1965-1990

A slight increase in temperatures has been recorded since the mid 1960s in north east England (Harris, 1985), though annual mean temperatures are still generally lower than the 1920s-1940s levels. Annual precipitation totals declined after the mid 1960s as did the frequency of flooding and size of flood peaks (Archer, 1981). Gauging station record suggest an increase in flood frequency and magnitude since the mid 1980s (Fig. 3.7). No major land-use changes date to this period.

The last 25 years appears to have been largely a period of channel bed vertical stability in the Tyne catchment. Low rates of fluvial activity characterised all three headwater tributaries studied, with only three flood units in Thinhope, Whitewalls and Knar Burns dating to this period and a significant reduction in the size of boulders deposited. At Broomhaugh Island and Low Prudhoe there has been accretion of fine-grained within-channel benches.

Summary

Since 1600 A.D. fluvial activity at all 3 study sites has been characterised by alternating periods of river bed incision and stability. Episodic changes in vertical channel stability appear to coincide with non-random decadal-scale fluctuations in flood frequency: three periods with distinct clustering of large floods (1740-1790, 1860-1899 and 1940-1965) were associated with vertical instability (channel trenching) throughout the Tyne basin, while intervening periods with relatively few exceptional floods were associated with channel accretion and floodplain rebuilding in general, but with significant spatial variation. The next section looks in detail at upstream-downstream relationships and variations in the in precise timing and nature of channel response as a function of catchment location.

Flood regime, channel entrenchment and sediment transfer

1. High magnitude floods and channel entrenchment

The response of the River Tyne to periods of increased frequency of high magnitude floods appears to have been relatively rapid and widespread, with channel trenching in headwater tributaries and main valley reaches. In detail, however, spatial variations in the precise timing and magnitude of river bed incision are apparent. Eighteenth century incision appears to have been more effective in headwater tributaries with progressively smaller depths of incision downstream. Two phases of incision in the late nineteenth century and mid twentieth century, however, show the opposite trend with the most marked erosion downstream at Broomhaugh and Low Prudhoe.

Hence, high rates of incision in the middle and lower Tyne valley followed the main phase of tributary channel entrenchment, and were probably partly a response to it. Headwater incision and network extension along with reduced floodwater storage would have increased the speed of runoff to the main channel and increased effective stream power downstream. Once incision had been initiated downstream a number of factors favoured rapid river bed erosion: large upstream drainage areas and associated discharges, especially downstream of the North/South Tyne confluence, relatively narrow channel widths, and relatively cohesive silty-sandy channel banks.

2. Periods of low flood frequency: episodic erosion and transfer of sediment

The timing and nature of fluvial adjustments during periods of low flood frequency appears to have been highly variable. Appreciable differences in channel behaviour in upper and lower reaches of the Tyne were probably related to the amount, calibre and quality of sediment available at each location.

i) Upper Tyne. A corollary of widespread, although episodic, river-bed erosion is enhanced production of coarse-grained sediment and, subsequently, downstream aggradation (cf. the negative feedback mechanism of Schumm's complex response model (Schumm, 1973)). This type of response appears to have been particularly significant in upper and middle reaches of the South Tyne following high rates of tributary and main channel trenching in the mid to late eighteenth century.

A considerable influx of bed-load calibre sediment at floodplain sites on major tributaries of the South Tyne (Blagill on the River Nent and Blackett Bridge on the River West Allen), dated on the basis of lichen and cartographic evidence to the 1840s, appears to have transformed them from single-channel to aggrading, braided rivers (Macklin and Aspinall, 1986; Macklin, 1986). Further downstream in the main South Tyne valley, large-scale aggradation and lateral channel instability at a series of alluvially-controlled "sedimentation zones" dating to the mid nineteenth century (Macklin and Lewin, 1989) was also associated with a significant influx of coarse sediment.

The concomitant deposition of fine-grained metalliferous sediments associated with upstream lead mining is likely to have aggravated instability by inhibiting vegetation stabilisation of sediments. Mining operations, however, did not release large amounts of <u>coarse</u> sediment into the river, except very locally (e.g. at Blagill, Macklin, 1986); the primary source of coarse sediment was most likely to have been tributary and main channel entrenchment.

The relative contributions of tributary and main channel sediment sources is difficult to assess without detailed lithological analysis. While the volume of material derived from individual tributary channels is likely to have been relatively small, their combined contribution may have equalled that of the trunk stream, although there would have been some delay in tributary-derived coarse sediment reaching the main valley. Significant channel transformation and lateral channel instability in the South Tyne appears to have been initiated in the 1840s, several decades after major trenching upstream. The first part of the nineteenth century was a period of low flood frequency (5 documented floods for the River Tyne between 1793-1823, and only 2 dated flood deposits in Thinhope), with few competent flows. It is therefore likely that sediment was temporarily stored within tributary valleys and at tributary/main channel junctions with little downstream transfer. Increasing frequency of moderate floods, however, between 1824 and 1842 enabled this material to be redistributed.

ii) Middle and lower Tyne. Lag times for channel adjustment following phases of incision in the late nineteeth and mid twentieth centuries appear to have been relatively short in lower reaches of the Tyne compared to upstream. A wide range of flow discharges would be capable of transporting the predominantly fine-grained sediment and channel recovery/re-filling (deposition of within-channel benches) starts soon after incision has ceased. High rates of within-channel deposition recorded at Broomhaugh and Low Prudhoe (see Tables 4.3, 6.1) following channel incision appear to be related to increased supply of sediment and decreased overbank sedimentation.

Channel entrenchment has had 2 main consequences for supply of fine-grained material. Firstly, enlarged headwater channels appear to have not only increased floodwater discharge downstream but also enhanced the conveyance of fine-grained sediments. Secondly, river bed incision is likely to have had a significant impact on bank stability in the Tyne valley. The direct increase in bank elevation resulting from bed erosion may exceed the critical height for mass failure (Thorne and Osman, 1988). Also exposure of non-cohesive gravel-dominated deposits beneath cohesive silts and sands (common in middle and lower reaches of the Tyne) has made channel banks more prone to undercutting and mechanical failure of cantilevers (cf. Thorne and Lewin, 1979). Fine-grained bank debris disaggregates very quickly (Thorne and Osman, 1979) and can contribute significant amounts of sediment to the channel.

The combination of river bed incision and accretion of lateral benches within the channel has resulted in a deeper, narrower channel in the middle and lower Tyne valley, and an increase in channel capacity. This has lead to a progressive reduction in overbank sedimentation over the last 100 years or so.

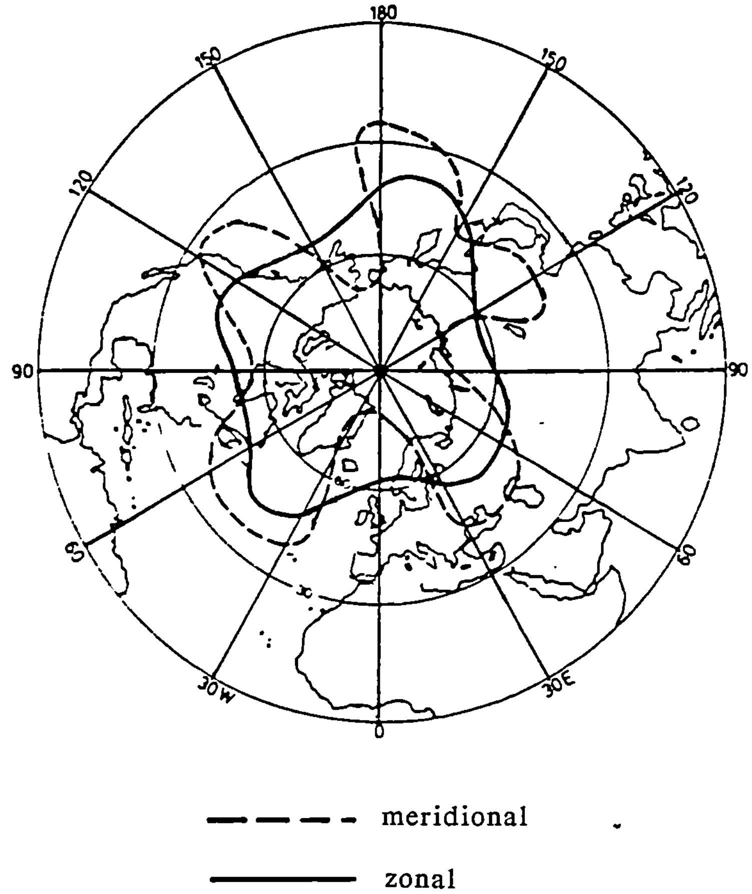
Short-term climate change and secular trends in flood frequency and magnitude

Non-random temporal variations in the flood regime of the River Tyne over the last 3-400 years have important implications for river response. The effectiveness of individual flood events is increased during periods with increased frequency of large floods. A possible causal mechanism for decadal-scale fluctuations in flood regime is short-term climate change (e.g. Knox, 1984). This is examined in detail below.

The timing of major changes in flood frequency in the Tyne basin correspond with trends identified in long-term flood records that have been reconstructed (from documentary/hydrological evidence) for 2 other British rivers; the River Tweed, Scotland (McEwen, 1990) and the Upper Severn, Wales (Higgs, 1987a; Howe, Slaymaker and Harding, 1967).

Synchrony in the timing of major trends in precipitation patterns and flood regime over sizeable areas has been linked to large-scale atmospheric circulation patterns (e.g Hirschboek, 1987; Knox et al, 1975); principally the configuration of circumpolar upper air waves (the circumpolar vortex) in the northern hemisphere (Lamb, 1982). The circumpolar vortex tends to alternate between two specific forms, zonal and meridional (Dzerdzeevskii, 1968; Hirschboek, 1988; Kutzbach, 1970; Knox et al, 1975; Lamb, 1977), that determine local synoptic conditions and hence the duration, intensity, distribution and type (rain or snow) of precipitation (Hirschboek, 1987: Knox et al, 1975). While the precise mechanisms for changes in atmospheric regime are not known in detail (Ford, 1982), the major control on the strength, pattern and position of circumpolar flow is temperature (Lamb, 1982). Under warmer conditions flow is strongly zonal (west to east) with low amplitude, widely spaced waves (Fig. 7.2). In cooler periods, however, the lateral temperature gradient is steepened favouring more frequent and enhanced occurrences of north/south (meridional) wind patterns in mid latitudes and southward displacement of the main air streams, with increased amplitude and number of meanders in the circumpolar vortex (Fig. 7.2).

The timing of changes between the 2 configurations for the period 1861-1971 has been established using the Lamb catalogue of daily weather types over the British Isles (Lamb, 1972). The frequency of westerly weather types is directly



<u>Figure 7.2</u> Comparison of meridional and zonal configurations of the circumpolar vortex (from Lamb, 1981)

related to the degree of zonality in the upper atmosphere (Lamb, 1977), whereas, northerly and southerly weather types are associated with meridional conditions. In Fig. 7.3 yearly frequencies (in total number of days as a percentage of the year) of westerly weather types since 1861 are plotted with an index of meridionality (derived from the Lamb catalogue by Murray and Lewis, 1966). Two major break points are apparent, at around 1900 and 1940. More meridional conditions seem to have prevailed before 1900 and after 1940 while the period 1900-1940 was characterised by strongly zonal conditions. These break points correspond to major changes in flood regime identified on the River Tyne, with clustering of exceptional floods occurring in periods dominated by meridional circulation patterns.

Although detailed weather data are not available for the period before c.1860, the principal features of the prevailing large scale upper atmosphere circulation have been inferred from regional temperature and precipitation records (Lamb, 1977; 1982). During the Little Ice Age climate zones in the Northern hemisphere shifted southwards towards the equator (Lamb, 1982). High amplitude waves in the circumpolar vortex pushed polar air masses over Britain, resulting in high frequency of northerly (meridional) weather systems. Exceptional floods in the mid-late eighteenth century appear to have coincided with particularly strong meridional circulation patterns.

Above average annual rainfall totals over the Tyne catchment (Fig. 3.6) have occurred in both meridional and zonal periods; indeed the highest totals were recorded in the 1920s associated with strongly zonal circulation. Important differences exist, however, in the nature of precipitation (duration, intensity and type) associated with each condition that affect hydrological response. In general, higher intensity rainfall events are more likely during episodes dominated by meridional circulation patterns, while lower intensity events more likely during zonal periods. Extreme high amplitude waves in the circumpolar vortex, characteristic of meridional patterns, can create stationary blocking situations

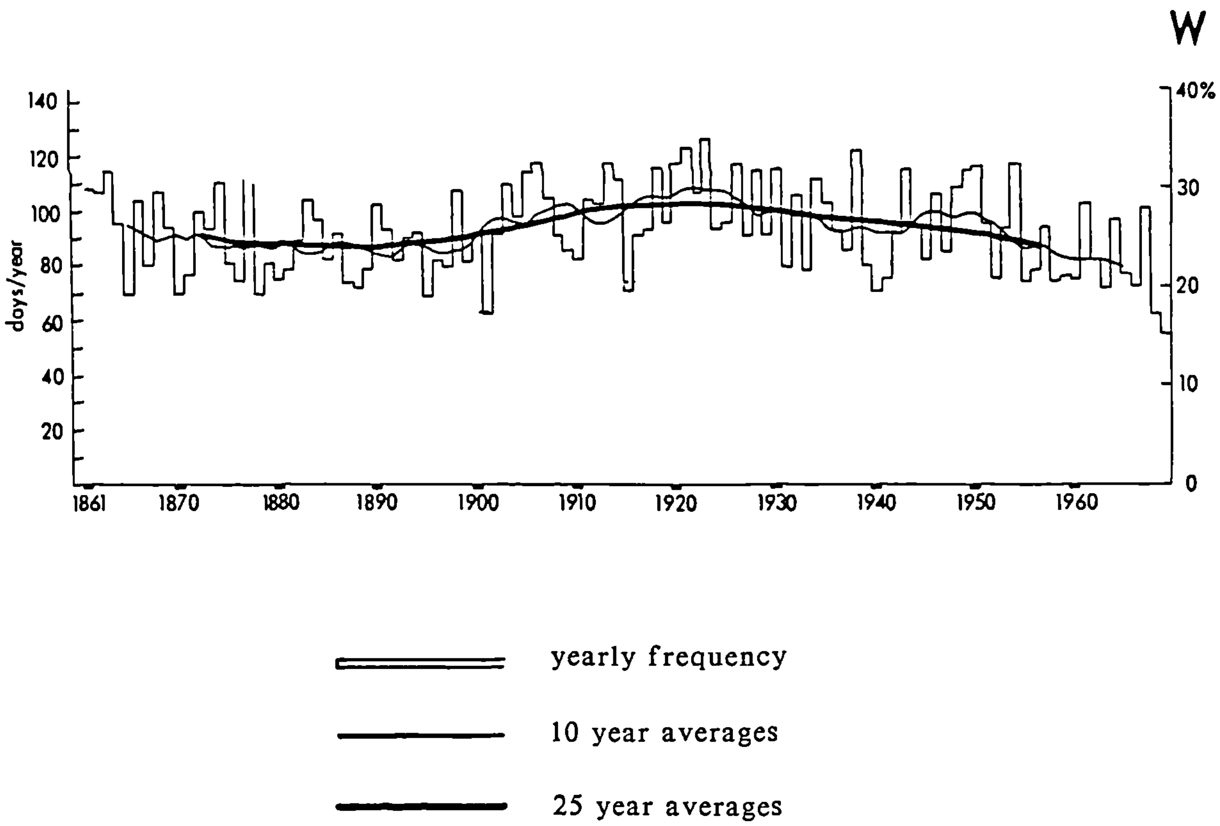


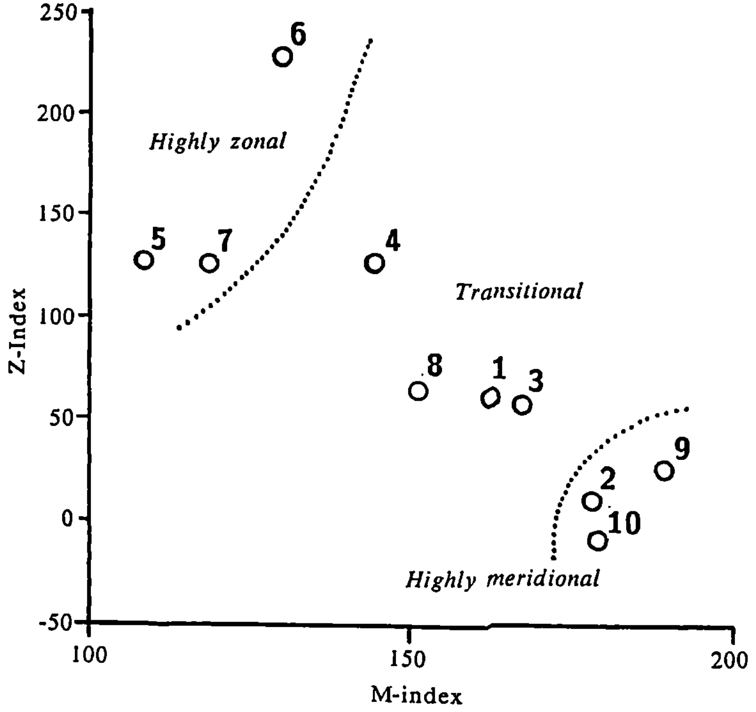
Figure 7.3 Frequencies of westerly weather systems over Britain since 1861 (from Lamb, 1972)

which are favourable for the occurrence of unusual (high intensity, multiple peak) rainfall events (Bleasdale, 1970) associated with many extreme floods (McEwen, 1989; Hirschboek, 1987).

Temperature, through its control on evapotranspiration rates and soil water conditions, is also an important influence on hydrological response. Warmer temperatures prevail during zonal periods, for example the strongly zonal period of the early twentieth century was coincident with the world thermal maximum (Lamb, 1977). In contrast, meridional periods, dominated by northerly/polar air masses, are considerably cooler. The lower rates of evapo-transpiration and higher soil wetness associated with the latter condition, are likely to promote rapid runoff and large flood peaks. An additional consequence of colder temperatures is increased likelihood of snowfall. Many of the largest catchment-wide floods on the Tyne have resulted from snow-enhanced events, e.g. 1947, 1955, 1963.

In summary, non-random variations in flood frequency on the River Tyne appear to be related to decadal-scale fluctuations in the configuration of the upper atmosphere. Synoptic weather conditions associated with meridional circulation patterns favour extreme precipitation events leading to high magnitude floods. An important corollary, given the relationship between large floods and channel trenching, is that vertical channel instability in the Tyne catchment is associated with meridional configurations of the upper atmosphere. This interpretation is supported by Fig. 7.4 which plots indices of meridionality and zonality for decades since 1873 (From Murray and Lewis, 1966) with trends in fluvial behaviour. Periods of marked channel incision have the highest meridionality values and episodes of lateral re-working/sedimentation in the River Tyne coincide with high zonality. Interestingly, low rates of fluvial activity correspond to periods of transition/change in the configuration of the atmosphere.

Archer (1981) has demonstrated important differences in the seasonal flood regimes of the South Tyne, North Tyne and Lower Tyne for recent/gauged floods (Fig. 7.5). The greatest contrasts occur in late summer, and for higher return period



RIVER BEHAVIOUR

Thinhope	Broomhaugh	Low Prudhoe	
Lateral reworking	River bed stability		5 1910-19 6 1920-29 7 1930-39
Aggradation of coarse flood sediment	Rapid rates of within-channel vertical accretion		
Low rates of fluvial activity			1 1873-79 3 1890-99 4 1900- 09 8 1940-49
Minor river bed incision	Slow rates of within-channel sedimentation		
River bed incision	Rapid rates of river bed incision		2 1880-89 9 1950-59 10 1960-64

Figure 7.4 Plot of atmospheric circulation indices for decades since 1873 (from Murray and Lewis, 1966), showing channel and floodplain behaviour at Thinhope, Broomhaugh and Low Prudhoe

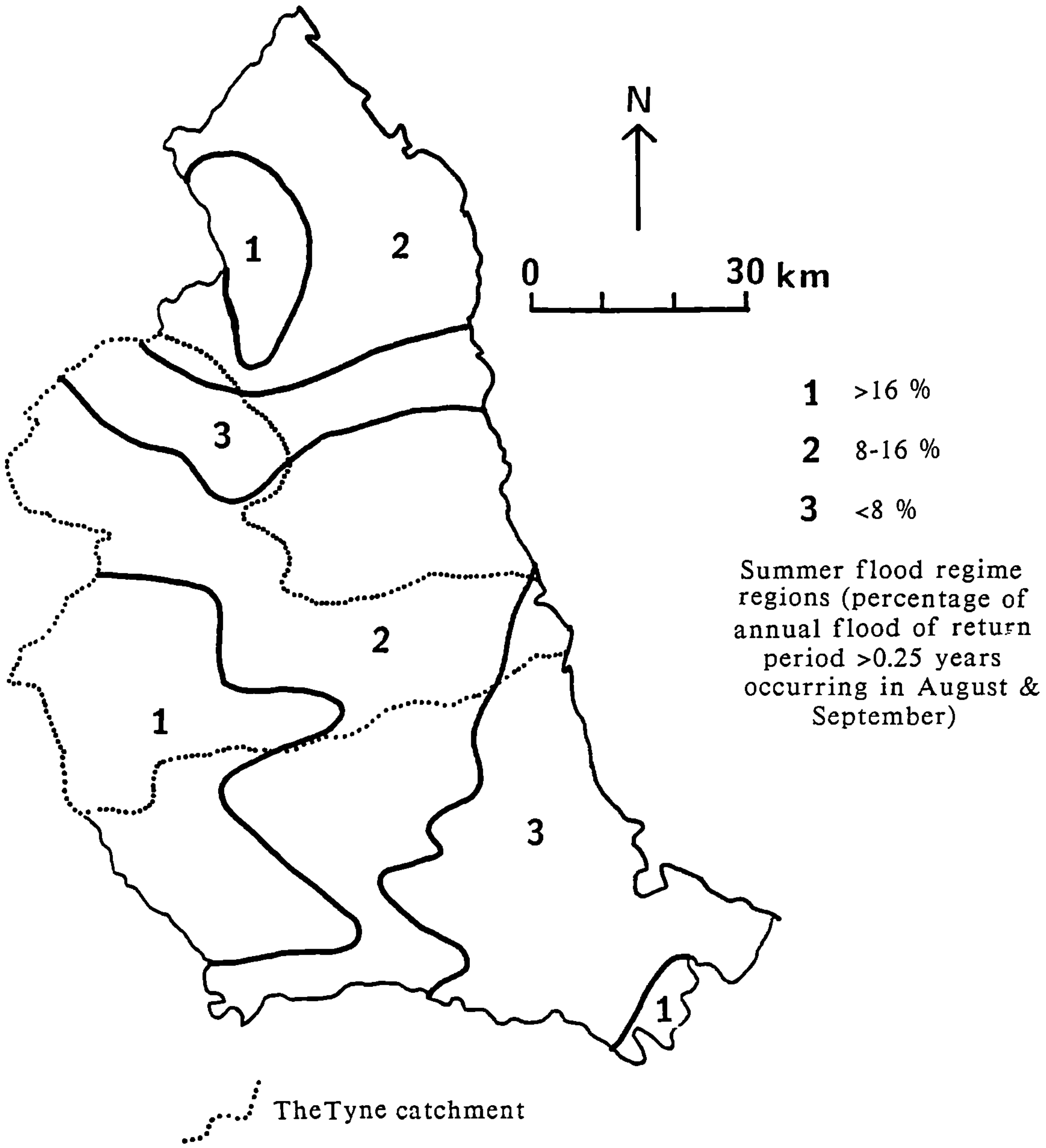


Figure 7.5 Seasonal flood regime in the Tyne catchment (from Archer, 1981)

events; over the last 30 years the South Tyne has experienced more floods in August and September and fewer between January and March compared to other parts of the catchment (Fig. 6, p.1031, Archer, 1981). If these patterns are characteristic of meridional periods in general, variations in the seasonality of exceptional floods may provide an explanation for disparate catchment responses, in particular asynchronous erosion in upper and lower parts of the Tyne Basin in the eighteenth century. A high proportion of floods in the early eighteenth century occurred in summer, corresponding with marked incision in upper South Tyne tributaries, but little downstream response. In contrast, a preponderance of Autumn events during the 1770s and 1780s was coincided with catchment-wide incision.

Although the above discussion suggest there is a direct relationship between circulation patterns, flood frequency and behaviour of the River Tyne over the last 400 years, various land-use practises have also been shown to have effected river activity at several locations. However, while anthropogenic land-use changes and channel modifications have effected rates of runoff and flood magnitudes, they have not influenced the temporal distribution of flood events: their impact would appear to be one of increasing the sensitivity of the Tyne to small-scale climate changes and reinforcing the climatic signal.

Implications for longer-term alluvial development and interpretation of Holocene alluvial sequences

Enhanced rates of erosion seems to have been characteristic of a range of environments in north and west Britain over the last 300 years (Ballantyne, 1991); significant valley floor incision has been recorded in north west England (Hooke *et al*, 1990) and mid Wales (Macklin and Lewin, 1986) and increased debris flow activity in north west England (Harvey and Renwick, 1987) and Scotland (Brazier and Ballantyne, 1989; Innes, 1983). Erosion has been variously attributed to climatic and/or anthropogenic causes, and a number of authors suggest random extreme events as a possible triggering mechanism (e.g. Innes, 1983). Climatically-controlled clustering of extreme events offers an explanation for initiation of widespread instability in the uplands.

In the context of longer-term alluvial development it is important to determine whether the nature and magnitude of climate changes and widespread instability over the last 300 years have been exceptional or if similar episodes have occured earlier in the Holocene. Longer-term circulation/climate patterns are indicated by figure 7.6 which plots frequencies of south-westerly surface winds over S.E. England since 1340 A.D., believed to be a reflection of large-scale upper atmospheric patterns over Britain as a whole (Lamb, 1972); high frequencies reflect zonal conditions. The frequency of westerlies was extremely low in the eighteenth century, indicating high meridionality, but there do appear to have been comparable levels earlier in the record, around 1450 and 1600 A.D. The period around 1450 A.D. was also characterised by fluvial erosion in the Tyne catchment (Macklin et al, in press).

This study provides information of utility in the interpretation Holocene alluvial sequences in terms of prevailing flood and climate regimes. Episodes of widespread channel degradation (identified by lateral discontinuities in river sequences: unconformable contacts, terrace edges) are believed to reflect increased frequency and magnitude of flooding, associated with cooler and wetter periods and meridional circulation patterns. While high rates of sedimentation and sediment transfer over the last 300-400 years have been associated with increased frequency of moderate floods under zonal circulation regimes (high wetness and relatively warm temperatures). Periods of vertical stability and relatively low rates of fluvial activity are likely to represent low moisture availability and low flood frequency, most probably associated with warm temperatures and zonal circulation patterns, but also possible under meridional conditions.

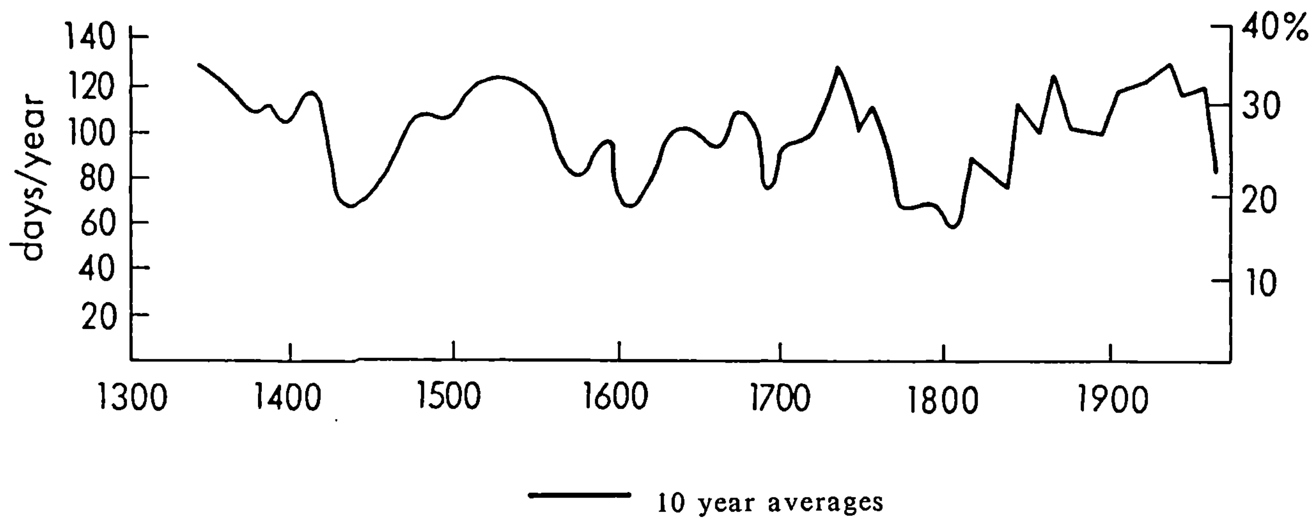


Figure 7.6 Long-term trends in upper atmospheric circulation patterns as indicated by the frequency of south-westerly weather systems over Britain (from Lamb, 1972)

Response of the River Tyne to future climatic changes

Given the marked channel and floodplain adjustments in the Tyne basin in response to small-scale climate changes over the last 300 years, it is likely that the catchment will be sensitive to future climate changes as predicted as the result of global warming (see chapter 2). Various scenarios exist regarding the nature and magnitude of change, however, if, as several studies suggest, there is an increase in both runoff totals (Palutikov, 1987) and storminess (Newson and Lewin, 1991) over north-east England, it is likely that vertical instability will continue to be important in the Tyne catchment. While entrenchment reduces the risk of severe overbank flooding, large inputs of eroded coarse sediment to lower reaches of the Tyne could cause widespread channel instability, similar to that experienced in the nineteenth century. Additionally, erosion and reworking of mining-age sediment would re-introduce large quantities of metal contaminated sediment into the system, posing a considerable pollution problem. An alternative scenario, however, given the relationship between increasing temperatures and high zonality, is that moderate, rather than high, magnitude floods will be dominant, allowing a period of floodplain re-building and channel infilling that would reduce channel capacity and hence increase the flood hazard.

Chapter 8

CONCLUSIONS

1. Nature of the sedimentary and morphological flood record of the River Tyne

The morphological form and sedimentary properties of coarse flood sediments in headwater tributaries of the River Tyne appears to be strongly related to flood water:sediment ratios that is primarily controlled by sediment supply. Bars, sheets and splays are deposited under Newtonian flow conditions from flows with relatively low sediment concentrations. Boulder berms and lobes are associated with quasi-Newtonian flows with high sediment loads.

Flood sedimentation in lower reaches of the Tyne comprises vertical accretion of fine-grained, well-bedded alluvial deposits at overbank and within-channel locations. Larger floods can be identified on the basis of textural discontinuities that reverse the overall fining upward sequence. The high sand component in within-channel fines, together with regular textural reversals, may be usuful criteria by which they can be distinguished from floodplain sediments deposited soley by overbank flood events.

2. Flood magnitude estimates

In Thinhope Burn a number of factors complicate the straightforward application and interpretation of competence-based discharge estimates. Most importantly, given that both the extent of post-flood erosion and the proportion of valley floor inundated during an event are unknown, palaeoflow width and depth estimates can only be considered as approximate estimates. All four equations used indicate a decrease in flood magnitude since the late eighteenth century, although a very wide range of discharge estimates are provided by each method. Progressive and continuing confinement of Thinhope Burn within its own alluvium, however, has markedly reduced the availability of coarse sediment and hence sets an additional constraint on flow competence and magnitude estimates employing boulder size measurements in more recent flood events.

Estimation of flow magnitude asociated with deposition of fine-grained flood sequences at downstream locations is also difficult. While, in general, coarser and thicker units are deposited in larger floods, changes in sediment supply and relative surface elevation are also important controls on the nature of sedimentation. In vertically dynamic river reaches such as Broomhaugh and Low Prudhoe, it is essential to determine precisely the timing, magnitude and location of river bed incision before relative discharges can be assessed.

3. Flood frequency estimates

This study has confirmed the utility of trace-metal dating of fine-grained flood sediments and lichenometric dating of coarse-grained units. These methods have enabled detailed and temporally well-defined records of flooding over the last 300-400 years to be established for a range of locations in the Tyne catchment. Distinct clustering of floods is apparent at upland, piedmont and lowland reaches of the River Tyne with increased frequency of large floods between 1740-1790, 1860-1899 and 1940-1965, and reduced frequency in the intervening periods.

4. Response of the River Tyne to flood frequency and magnitude variations since 1600 A.D.

The response of the River Tyne to periods of increased frequency of high magnitude floods appears to have been relatively widespread and rapid, with channel trenching in headwater tributary and main valley reaches. In contrast the timing and nature of fluvial adjustments during periods of low flood frequency appears to have been more variable. Appreciable differences in channel behaviour are apparent in upper and lower reaches of the Tyne, related to the amount, calibre and quality of sediment available at each location. Enhanced availability of coarse-grained sediment following river-bed incision in the upper South Tyne during the eighteenth century promoted significant channel transformation and lateral instability in lower reaches in the mid nineteenth century. The delay between sediment production and downstream transfer was due to a lack of competent flows in the early nineteenth century. Channel adjustment in middle and lower reaches of the Tyne following phases of incision appears to have been more rapid. A wide range of discharges would be capable of transporting the predominantly fine-grained sediment and channel refilling (deposition of within-channel benches) starts soon after incision ceases. High rates of within-channel sedimentation appear to be related to increased supply of sediment and decreased overbank sedimentation.

The rapid rates of vertical channel and floodplain adjustment in the Tyne catchment over the last 400 years are unusual in comparison with the behaviour reported in other British rivers over this period. Newson and Macklin (1990) have suggested that marked vertical responses to flooding may be restricted to catchments, like the Tyne, dominated by sandstone lithologies with limited river incision in basins developed on shale. However, many previous studies in these latter catchments have been based on cartographic evidence and tended to emphasise channel and floodplain planform development (e.g. Lewin et al, 1983) rather than vertical changes. Further work is required, on a variety of lithologies, to determine the range of river responses to episodic flood frequency and magnitude variations.

5. Effects of short-term climate change on flood frequency and magnitude in the Tyne Basin

Distinct clustering in the timing of large floods in the Tyne catchment corresponds with decadal-scale hydroclimatic changes, associated with fluctuations in the configuration of the upper atmosphere. Synoptic conditions during periods characterised by relatively low mean annual temperatures and meridional circulation patterns (e.g. precipitation extremes; atmospheric blocking) favour extreme floods. Intervening periods dominated by zonal circulation patterns and warmer temperatures favour lower intensity/magnitude rainfall events and hence there are fewer exceptional floods.

Anthropogenic land-use changes and channel modifications have effected rates of runoff and flood magnitudes, but not the temporal distribution of flood events. Their impact would appear to have been one of increasing the sensitivity of the Tyne to small-scale climate changes and reinforcing the climate signal.

6. Sources and sinks of flood sediment

Marked temporal and spatial variations in the production and transfer of sediment in the Tyne catchment over the last 400 years have resulted from decadal-scale fluctuations in flood regime and fluvial behaviour. Periods of enhanced production and transfer of sediment associated with channel entrenchment have alternated with periods of low flow frequency and low rates of fluvial activity. Extrapolation of sediment transport rates derived from single sites or short time periods is thus inherently unreliable; long-term sediment budgets need to be considered at a reach or catchment scale.

Many river systems in Britain have shown a tendency towards incision over the Holocene, with a net loss of sediments to estuarine and near-shore depositional basins. Off-shore sedimentary sequences, therefore, potentially hold the key to total sediment budgeting. In order to trace alluvial sediments off-shore it is essential to characterise lithological, mineralogical and geochemical signatures of sediment sources within individual river basins. Sediment sourcing also allows variations in the location and timing of erosion within catchments to be distinguished. Within the Tyne basin, for example, the distinct geologies of the North and South Tyne catchments provide very different sediment geochemistries, allowing differentiation between North and South Tyne flood events in alluvial sequences in the lower Tyne and, possibly, offshore.

7. Implications for engineering design and river and floodplain management.

Short-term (<100 years) climate changes, associated with atmospheric circulation adjustments, generate non-random trends and variations in flood series, invalidating the underlying assumption of flood frequency analysis (i.e. that floods are distributed randomly in time). Floods occuring under different climatic regimes belong to different populations and hence flood series should not be extrapolated beyond the (short) climatic period in which they were derived. It is essential, therefore, to put flood series in their correct hydroclimatic perspective, and that *"floods are treated as real world physical events occuring within the context of a history of climatic variations in magnitude and frequency"* (Hirschboek, 1988). This study has demonstrated that floods also need to be considered in the context of a dynamic, responsive river system. Significant episodes of vertical and lateral channel instability in the Tyne Basin have been associated with changes in hydroclimate regime over the last 400 years. Changing channel morphology and cross-sectional area alters stage-discharge relationships and the flood hazard at a site. As a result of channel entrenchment at Broomhaugh and Low Prudhoe, for example, progressively larger floods are required to inundate the "floodplain", reducing the need for flood protection. In rivers that respond like the Tyne there seems little point in structural flood protection measures. Conservation and set-aside for river corridors would appear to be a more realistic alternative.

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APPENDIX I: DOCUMENTED FLOODS IN THE TYNE CATCHMENT, 1600-1990

Date	Catchment Location N	S	L	U	Comments
1660			x		
1674				x	
1698			x		
1701			x		
08.07.1722		x	x		Not known for many years
12.05.1728			x		
11.12.1733	x		x		
24.08.1752	x*		x		*Not remembered for 40 years
17.02.1753			x		Higher than for many years past
09.11.1760			x		
11.07.1761			x		
10.11.1761		x*	x		*Much damage
01.12.1763			x		6' lower than 1771
21.07.1766		x			
10.11.1766			x		
28.06.1770			x		
17.11.1771	x	x	x		Largest documented flood
26.09.1772		x			
06.1777				x	
26.10.1777		x			
1778			x		
10.03.1782	x	x	x		2'lower than 1771
17.11.1783			x		
10.10.1787				x	
19.07.1789			x		
16.07.1792	x*		x		*Rede 1' higher than 1771
18.08.1796				x	
06.06.1807	x*		x		*15' rise at Haughton
12.08.1809			x		
16.12.1814	x		x		Largest since 1771
30.12.1815		x	x		Large flood, nearly as much damage as 1771
18.07.1818	x				
02.02.1822			x		
10.10.1824			x		
25.12.1824			x		
27.02.1827			x		
13.07.1828			x		
01.12.1828			x		Largest since 1815
24.07.1829	x	x*	x		*As high as 1815
13.10.1829			x		Flood & spring tide
09.02.1831			x		Not quite so high as 1815
08.09.1832				x	
14.05.1833		x	x		
10.01.1834			x		
21.11.1835	x		x		
29.07.1836			x		
10.01.1837			x		Higher than any flood since 1815

APPENDIX I (cont...)

15.09.1839	x		x		
07.10.1841			x		Derwent highest since 1771
1842		x			
03.10.1845		x	x		Higher than any in last 40 years
05.07.1852		x			
16.12.1852		x	x		Like not occurred for 18 years
01.08.1854			x		
28.09.1856	x	x	x		One of highest in almost living memory
08.12.1856			x		
04.02.1862			x		Few inches higher than 1868
16.05.1864			x		
31.05.1865		x			
04.02.1868	x	x	x		Lower than 1856
08.02.1869			x		
18.06.1872		x			
20.08.1877	x	x	x		Wettest summer for 50 years
06.11.1877			x		
20.01.1878		x	x		
31.12.1878			x		
06.03.1881	x	x	x		Not so high since 1856 at Hexham
21.01.1883	x	x	x		
29.011886				x	
06.11.1886	x	x	x		
13.08.1890			x		
25.08.1891			x		
02.09.1892		x	x		
08.10.1892			x		
03.08.1895		x			
06.10.1900		x			R. Allen highest since 1771
26.10.1900		x	x		
08.10.1903	x		x		Biggest for 45 years at Hexham
24.11.1904			x		
30.01.1906			x		Highest since 1771 at Bywell
09.06.1907	x		x		
14.05.1911	x				
06.1912	x	x			
01.11.1919				x	
13.11.1923		x	x		Biggest for 20 years at Hexham
30.12.1924	x*	x	x		*Highest in living memory
20.09.1926	x	x	x		
23.07.1927	x				
24.09.1927		x	x		
10.08.1929	x				
10.11.1929		x	x		

APPENDIX I (cont...)

26.07.1930		x		
04.11.1931			x	
01.02.1933	x*		x	*Biggest since 1856
17.03.1934	x	x		
14.04.1934			x	
14.12.1936			x	
31.01.1937			x	
04.10.1938			x	
09.01.1939		x	x	
08.03.1941			x	
22.04.1947	x	x	x	3rd highest since 1771 at Bywell
20.08.1948			x	
04.04.1954		x		
08.10.1954	x	x		3" lower at Low Prudhoe than 1947
09.01.1955	x	x	x	Highest since 1771 at Hexham, 5th highest at Bywell
28.08.1956			x	
12.02.1958			x	
10.10.1960	x			Comparable to 1955 on upper N.Tyne
03.04.1962	x		x	
27.08.1962			x	
12.09.1962			x	Highest since 1955
06.03.1963			x	
21.11.1963	x	x		
07.12.1964	x*	x		*Higher than 1955 at Kielder
30.07.1965			x	
31.11.1966	x			
17.10.1967	x	x	x	
23.03.1968	x			
13.09.1968	x		x	
19.12.1968			x	
30.08.1975	x		x	
26.01.1977	x	x	x	
28.12.1978		x		
26.11.1979	x	x		
30.12.1979			x	
03.03.1981	x			
26.08.1986	x*	x	x	*6" lower than 1771 at Warden
04.02.1990	x	x		

KEY

N	North Tyne
S	South Tyne
L	Lower Tyne
U	Unspecified

APPENDIX II: **HEAVY METALS AND L.O.I DATA FOR LOW PRUDHOE SECTION**

Depth (cm)	LOI %	Heavy metals ($mg\ kg^{-1}$) Pb	Zn	Cd	Mn	Cu	Fe	Ag
1.0	7.0	778	763	1.7	760	46	21150	2.8
3.0	4.3	761	590	1.1	697	37	16260	2.8
5.0	3.1	837	552	0.9	791	37	20900	3.6
7.0	3.5	786	488	0.8	728	44	21830	4.8
9.0	3.2	730	543	0.7	731	46	21420	4.3
11.5	5.4	1537	910	1.4	978	45	22540	5.1
13.5	3.9	1465	949	0.8	931	49	20300	6.0
14.5	4.4	1694	1219	3.5	1058	51	24130	1.8
16.0	5.8	1660	1239	3.5	1057	45	25450	2.1
18.0	7.8	1388	1167	3.3	1032	40	24320	2.4
20.0	4.9	1573	959	3.0	845	43	23630	2.5
22.5	5.4	2007	1458	3.7	1152	37	26470	2.8
25.2	4.5	1738	1083	3.0	948	38	24760	2.0
27.5	6.0	2307	1486	4.0	1245	47	26500	3.2
29.5	5.5	2211	1283	3.9	1139	41	24630	3.1
31.2	5.1	1463	1106	3.9	985	44	26010	3.0
33.5	4.3	923	980	3.7	702	40	23510	3.1
36.0	4.6	1286	1253	4.3	856	80	24830	2.9
38.0	4.0	1121	1052	4.2	719	33	23220	3.5
40.5	5.8	1168	1213	4.6	784	34	20670	3.3
42.5	4.4	879	958	4.0	596	44	20120	3.2
44.2	2.9	829	848	4.2	582	35	22140	3.5
46.2	3.3	910	854	4.0	635	30	13170	3.8
47.7	3.1	805	776	3.9	576	32	20310	3.6
49.2	2.8	709	3409	4.6	512	23	20800	3.6
51.0	2.3	620	668	2.5	511	30	20220	0.9
53.0	2.1	722	720	2.9	567	38	20940	0.9
55.5	2.6	490	1196	2.9	467	31	17430	0.6
57.0	3.1	1275	1355	3.5	1054	35	20340	0.7
59.0	2.8	32	25	3.6	25	33	21860	0.4
59.5	2.4	679	731	3.5	598	32	20540	0.7
60.5	3.7	831	794	3.9	656	38	22230	0.5
62.0	3.2	813	708	3.8	568	31	21390	1.0
64.0	2.7	817	716	3.8	578	38	20660	0.9
66.5	2.1	354	576	2.6	444	36	16520	1.0
68.8	2.9	394	585	2.7	462	31	12340	0.9
69.7	3.2	466	879	3.2	478	31	19640	0.9
71.2	2.7	504	626	2.7	438	22	15900	0.5
72.7	2.6	619	4838	5.6	574	12	20250	0.5
74.2	2.5	533	1431	2.8	501	11	18750	0.3
75.5	2.7	562	703	3.3	547	42	18170	0.6
77.5	2.6	450	597	3.2	520	34	17700	0.6
79.5	2.8	427	606	3.5	501	40	20270	0.4
80.5	2.8	461	665	2.8	525	36	21090	0.8
81.5	2.5	403	609	2.6	475	29	16190	0.5
82.5	2.6	469	1001	2.8	481	27	20140	0.7
83.5	2.8	463	639	2.5	438	33	19920	0.4
84.5	2.2	387	622	2.4	484	29	19200	0.5
86.0	2.3	459	622	2.4	473	38	19980	0.6
88.5	1.9	190	424	2.0	268	20	9830	0.3
91.0	1.5	186	391	1.9	414	27	13820	0.3
92.7	2.1	248	442	2.4	529	45	20010	0.6
94.2	2.4	469	515	2.5	562	30	7390	0.7

APPENDIX II (cont...)

95.7	2.4	560	499	2.1	454	22	19010	0.2
97.2	2.0	362	472	2.3	526	32	10530	0.1
99.7	2.0	481	552	3.1	601	38	21960	0.3
102.7	3.0	459	524	3.2	590	34	23470	0.1
104.8	1.4	149	335	2.4	399	31	20060	-
105.7	-	429	489	2.9	551	31	21100	-
107.3	2.9	163	753	3.4	570	30	23180	-
108.2	2.3	352	388	2.7	479	29	17290	-
110.2	2.4	292	384	2.0	492	28	19650	-
112.2	2.2	238	434	2.2	461	30	20180	0.1
113.7	1.9	267	365	2.4	463	27	16560	-
115.5	2.1	335	406	2.5	507	18	21350	-
117.5	2.5	329	4185	2.8	452	11	20010	0.1
119.2	3.7	730	864	2.8	672	15	22800	0.4
121.7	3.4	536	4167	3.5	620	19	22000	0.4
124.5	3.5	477	4073	3.7	584	26	20030	0.2
126.0	2.7	522	4375	3.2	595	12	21020	-
126.7	4.1	509	587	2.2	629	10	17380	0.1
127.5	1.8	482	3373	2.3	518	18	17730	0.2
129.0	3.5	512	3409	3.1	598	12	21220	-
130.5	3.7	308	347	2.1	389	10	11890	0.3
132.0	2.1	294	383	2.2	510	11	26670	0.4
133.5	2.1	300	4057	2.7	398	10	12350	0.3
134.7	1.9	240	2621	1.7	361	-	8410	0.4
136.0	2.4	269	3810	2.1	366	8	22970	0.7
137.5	4.3	600	578	2.1	493	12	22300	0.8
139.2	3.5	468	3380	2.0	605	11	16410	1.1
141.0	3.9	525	3327	2.1	724	12	15690	0.8
143.5	2.8	335	399	2.1	653	21	21570	1.2
145.7	4.4	345	475	2.0	676	12	20700	1.1
147.2	6.7	318	4169	2.9	439	28	9560	1.3
148.2	3.0	303	317	1.7	565	24	19430	1.4
148.7	3.9	364	308	1.6	623	19	17520	1.8
149.7	3.0	325	288	1.4	574	19	21620	0.3
151.2	4.4	452	358	1.5	657	22	21540	0.1
152.5	2.6	308	293	1.2	490	20	20980	-
154.0	3.6	426	354	1.3	737	22	22210	-
156.0	2.5	289	4160	2.0	489	13	20130	-
158.0	1.8	339	233	1.0	397	11	14170	-
159.7	2.6	330	4385	1.8	502	9	19780	-
161.5	3.8	407	4580	3.2	622	37	11100	-
163.2	3.0	419	3153	1.6	665	22	20510	0.1
164.7	3.0	377	364	1.1	503	13	13270	0.1
167.0	3.5	320	193	1.2	482	11	13970	-
168.0	2.9	300	4326	2.6	436	36	8120	-
169.5	3.6	413	198	1.1	580	14	19450	-
172.2	3.9	501	3340	1.6	722	14	21760	0.4
174.0	3.0	348	211	0.8	617	14	7290	0.6
176.5	4.1	493	514	1.1	789	18	20260	0.6
178.5	3.7	464	3448	1.9	600	17	21450	0.6
179.5	4.0	458	4542	3.1	725	17	22330	0.5
181.2	1.9	317	3507	1.2	520	8	19230	0.2
182.3	4.1	480	215	1.1	726	12	22700	0.2
183.7	3.8	473	3814	1.4	673	14	20210	0.5
184.2	2.6	334	169	1.2	570	15	19320	0.1
184.7	2.6	293	190	1.2	539	25	14990	-
185.5	2.2	269	172	1.1	525	16	20460	-

187.5	3.7	383	237	1.5	528	28	11950	-
190.0	3.6	401	4495	4.3	571	15	17800	-
191.7	2.4	430	3738	2.4	630	15	22010	-
193.5	5.1	466	237	1.2	595	13	21780	-
194.7	3.8	418	617	1.4	685	14	20780	-
195.5	1.7	289	3509	1.9	456	9	19070	-
196.2	2.3	291	400	1.4	556	19	18400	-
199.0	6.6	291	442	1.9	720	21	22930	-
201.5	2.3	330	396	1.6	581	20	20010	-
202.5	4.0	309	384	1.7	585	18	20900	-
203.5	4.6	397	379	1.7	714	20	20690	-
204.7	2.7	319	275	1.3	412	9	13840	0.6
206.2	2.3	243	579	1.1	336	10	15810	0.4
207.5	2.2	412	436	1.7	787	22	20740	0.1
209.2	3.5	395	364	1.4	695	20	21250	-
211.5	3.2	226	257	1.1	410	9	13150	-
213.5	8.9	513	370	1.4	881	20	22330	-
215.2	4.5	387	3449	1.3	766	34	22790	-
216.5	1.8	358	282	1.0	418	16	18060	-
217.2	1.7	254	233	0.9	355	19	9380	-
217.7	2.5	297	266	1.0	391	13	16470	0.3
218.2	2.4	297	291	0.9	422	23	20150	0.4
218.7	-	438	283	1.1	420	43	19150	0.1
220.0	2.2	373	613	0.7	496	7	18950	0.1
221.5	2.3	659	3117	1.3	431	75	16490	0.3
222.2	3.9	504	261	0.9	814	14	20700	-
224.2	1.1	302	229	1.0	464	3	16790	-
226.7	2.4	311	382	0.9	450	4	18300	-
228.2	3.7	542	848	1.1	659	23	20930	-
229.5	2.4	363	1360	1.1	337	3	8440	0.7
231.2	3.8	657	292	1.5	848	20	22200	0.6
233.5	3.2	1172	3876	1.6	538	1	8980	0.8
235.2	3.4	792	711	1.1	605	3	20180	0.7
236.7	3.1	598	275	1.2	508	3	20850	0.6
238.2	3.1	356	795	1.1	534	2	19550	0.3
240.0	2.6	568	314	1.2	710	2	19360	0.3

APPENDIX III: LICHEN AGE-SIZE DATA

R.geographicum agg.

1	2	3	4
118	209	200	4
101	220	200	4
100	198	200	4
100	198	200	4
99	229	223	2
85	198	200	4
76	159	200	4
73	167	200	4
70	192	200	4
70	149	200	4
56	174	290	2
53	158	200	4
51	162	263	-
48	158	263	-
48	131	-	-
47	161	200	4
45	116	263	-
45	116	440	3
45	130	440	3
44	100	440	3
43	131	223	0
39	116	263	-
38	106	200	4
34	119	176	-
33	126	440	3
33	130	263	-
32	118	263	-
32	95	263	-
30	151	440	3
28	78	200	4
22	91	263	-
21	107	263	-

H.tubercolosa

1	2	3	4
177	131	223	0
162	129	200	4
157	112	200	4
144	91	240	3
141	138	440	1
137	123	440	3
125	116	176	-
124	111	440	1
122	104	200	4
108	90	440	1
105	67	124	4
102	96	200	0
98	133	263	-
96	63	113	0
92	41	124	4
88	78	200	4
82	63	113	2
79	40	124	2
76	40	124	2
75	66	176	-
74	53	263	-
74	108	440	1
68	42	240	1
62	75	440	2
56	40	124	4
53	40	124	4
53	62	180	2
52	38	180	0
47	19	185	-
45	32	185	-
43	43	185	-
42	48	263	-
40	41	185	-
40	31	180	0
38	23	185	-
37	36	176	-
37	46	180	0
36	21	185	
36	26	263	-
36	32	124	0
35	57	180	2
30	10	180	0
25	25	124	4
23	17	263	-
22	14	263	-
20	13	440	0
20	12	185	-
17	20	180	4
16	12	263	-
14	10	180	0
13	23	180	2
10	11	180	0
10	7	180	0

KEY

1 Mean (of 3 largest) lichen tallus diameter (mm)
2 Age (years)
3 Altitude (m above O.D.)
4 Aspect (1=north; 2=east; 3=south; 4=west)

APPENDIX IV: LICHEN AND BOULDER SIZE DATA FOR FLOOD DEPOSITS IN THINHOPE BURN

Site No.	Lichen Size/Flood Date 1	2	3	4	Boulder Size 5	6	7
1	RG	58.7	1823	1815	628	890	134
2	RG	large	pre-1760		739	960	137
3	RG	65.3	1813	1807	513	720	148
4	--	----	----	----	---	---	--
5	HT	50.7	1947	1947	433	590	84
6	HT	43.0	1953	1954	385	460	34
7	HT	20.7	1972	1972	260	320	49
8	HT	55.3	1943	1941	375	480	55
9	HT	43.3	1953	1954	228	270	30
10	HT	58.0	1941	1939	454	580	61
11	RG	15.0	1939	1939	340	560	88
	HT	61.0	1939	----	---	---	--
12	RG	43.3	1854	1845	515	750	107
13	HT	55.0	1943	1941	290	390	49
14	--	----	----	----	---	---	--
15	RG	41.0	1860	1856	336	480	84
16	RG	38.7	1865	1856	314	380	45
17	--	----	----	----	548	770	93
18	RG	106.0	1782	1766	---	---	--
19	RG	14.3	1937	1939	392	600	100
	HT	61.3	1938				
20	RG	108.0	1783	1766	491	570	41
21	RG	42.0	1858	1856	---	---	--
22	RG	47.3	1845	1837	590	750	83
23	RG	45.5	1849	1845	469	580	90
24	RG	64.7	1814	1807	422	700	123
25	RG	17.0	1928	1924	494	620	79
	HT	73.7	1928				
26	RG	large	pre-1760		700	920	120
27	HT	70.7	1930	1929	346	420	42
28	HT	13.7	1977	1977	380	480	65
29	HT	50.0	1948	1947	482	630	77
30	HT	55.9	1942	1941	359	400	30
31	HT	44.3	1952	1950	290	380	58
32	RG	17.3	1927	1929	425	600	89
	HT	71.3	1930				
33	HT	56.7	1942	1941	364	460	73
34	HT	87.7	1916	1912	439	650	122
35	HT	52.7	1946	1941	345	440	70
36	HT	46.7	1950	1950	450	590	100
37	RG	42.3	1857	1856	468	560	64
38	RG	41.0	1860	1856	579	740	105
39	RG	76.7	1786	1782	654	1000	140
40	--	----	----	1912	537	700	112
41	RG	31.7	1883	1877	623	780	128
42	HT	70.7	1930	1929	505	820	130
43	HT	50.7	1947	1947	443	800	164
44	--	----	----	1924	437	500	48
45	RG	45.4	1829	1815	458	670	112
46	HT	43.3	1953	1954	553	790	133
47	HT	70.7	1959	1958	---	---	---

APPENDIX IV (cont...)

48	HT	35.3	1929	1929	674	850	73
49	HT	49.0	1948	1947	630	920	163
50	HT	72.0	1930	1929	582	820	97
51	RG	39.7	1863	1856	522	820	138
52	HT	58.3	1941	1939	394	600	89
53	RG	44.7	1851	1845	438	570	82
54	HT	43.0	1954	1954	338	450	53
55	HT	55.3	1943	1941	478	570	61
56	RG	76.0	1799	1792	571	830	128
57	RG	32.3	1882	1877	334	490	71
58	HT	46.3	1951	1950	329	440	47
59	HT	51.0	1947	1947	468	540	51
60	HT	13.7	1977	1977	294	370	52
61	HT	55.7	1943	1941	340	460	62
62	HT	49.7	1948	1947	302	380	45
63	HT	43.3	1953	1954	---	---	--
64	--	----	----	----	---	---	--
65	--	----	----	----	---	---	--
66	RG	79.0	1796	1792	568	900	142

KEY
1 Lichen type (RG=*Rhizocarpon geographicum* agg.; HT=*Huilia tubercolosa*)
2 Lichen size (average of 3 largest in mm)
3 Lichen date
4 Assigned flood date
5 Mean boulder size (of 10 largest b-axes in mm)
6 Maximum boulder size (b-axes in mm)
7 Standard deviation of boulder size (b-axes in mm)

APPENDIX V: DATA FOR FLOW MAGNITUDE ESTIMATES, THINHOPE

(i) Site characteristics

Site No.	Flood Date	Slope ($m\ m^{-1}$)	Width (m)	Depth (m)	d*
2	>1760	0.240	15.0	1.8	739
39	1782	0.003	45.0	1.7	654
66	1792	0.020	22.5	1.4	568
1	1815	0.129	12.5	1.2	628
22	1837	0.036	22.0	1.0	590
51	1856	0.026	5.0	1.3	522
40	1912	0.056	7.5	1.0	537
25	1924	0.018	7.5	0.8	494
48	1929	0.089	15.0	1.2	674
52	1939	0.013	6.0	0.6	394

* Mean b-axis of 10 largest boulders (mm)

(ii) Additional particle size data used in calculations using Bathurst's equation

Site No.	(1a) d_r	(1a) d_{84}	(1a) d_{16}	(1b) d_r	(1b) d_{84}	(1b) d_{16}
2	100	181	62	265	388	169
39	84	181	47	294	416	205
66	108	147	71	265	388	169
1	100	181	62	294	416	205
22	90	168	56	294	416	205
51	87	159	44	294	416	205
40	84	181	47	265	388	169
25	90	168	56	265	388	169
48	104	164	47	265	388	169
52	87	159	44	294	416	205

KEY
1a based on active stream bed sediments
1b based on historic stream bed sediments

d_{84} particle size diameter (mm) for which 84% are finer
d_{16} particle size diameter (mm) for which 16% are finer
d_r reference particle size diameter (mm)

APPENDIX V (cont...)

(iv) Boulder size data combined for dated floods

Flood Date	Mean B-Axis (mm)	Standard Deviation (mm)
>1760	700	120.5
1766	739	126.9
1782	654	139.2
1792	664	121.7
1807	581	93.7
1815	661	107.7
1837	590	83.4
1845	579	72.2
1856	651	95.6
1877	628	121.2
1912	608	52.8
1924	534	54.6
1929	725	74.3
1939	546	44.8
1941	493	45.5
1947	689	142.6
1950	470	76.0
1954	580	101.2
1972	260	49.0
1977	389	55.7

APPENDIX V (cont...)

(iii) Calculated discharges

Site No.	1a	1b	2	3	4
2	3.19	9.26	22.42	47.71	2.70
39	849.09	1001.83	135.75	127.14	553.03
66	98.38	189.08	42.01	48.79	34.53
1	4.80	16.34	14.33	24.43	3.39
22	29.94	115.97	26.37	34.74	19.71
51	7.79	34.83	8.46	9.65	5.29
40	4.51	19.69	8.55	11.29	3.89
25	20.43	65.99	8.40	8.67	10.67
48	7.75	26.26	18.02	30.37	6.46
52	18.08	73.77	5.60	4.64	8.81

KEY TO EQUATIONS USED
1a Bathurst 1988
1b Bathurst 1988
2 Carling 1986
3 Williams 1983
4 Williams 1983

APPENDIX VI: HEAVY METALS AND L.O.I. DATA FOR BROOMHAUGH ISLAND CORES

CORE A

Depth (cm)	LOI %	Heavy metals ($mg\ kg^{-1}$) Pb	Zn	Cd	Cu	Mn	Fe	Ag
5	9.45	2164.7	1746.4	6.5	30.7	1622	25914	2.73
15	4.17	1479.6	1514.2	4.9	13.7	1123	21500	2.15
25	3.92	633.6	1004.6	3.3	9.8	869	15576	1.06
35	3.24	333.2	574.7	2.1	7.5	713	12679	0.71
45	4.45	659.4	904.2	3.2	12.3	859	18807	1.20
55	2.58	246.0	452.7	1.6	6.7	741	14042	0.79
65	2.44	165.4	117.9	0.9	5.7	617	9814	0.59
75	2.94	332.9	82.1	1.2	5.9	689	12232	0.55
85	2.75	184.4	72.8	0.9	5.1	635	10052	0.56
91.5	3.46	278.8	305.5	1.9	8.1	746	17074	0.81
95	3.71	302.1	463.1	2.5	8.7	884	18496	1.41
99.5	3.49	349.0	112.8	1.6	5.8	520	15803	0.88
103.5	2.12	241.5	74.6	1.4	4.7	481	9972	0.31
110	2.52	285.5	65.3	1.5	5.2	615	11597	0.51
116.5	1.73	344.5	48.0	2.5	6.2	436	9945	0.56
119.5	2.16	129.6	82.6	1.7	5.8	699	13679	0.77
125.5	1.83	233.0	90.7	1.2	5.2	569	13177	0.65
135	2.18	138.1	75.3	0.6	3.6	325	8242	0.35
144.5	3.28	560.2	176.6	1.1	6.3	611	10681	0.77
150	2.51	189.2	215.5	1.7	6.9	686	12566	0.39
160	1.68	238.0	76.9	0.7	4.5	545	10062	0.47
170.5	2.71	405.9	64.5	1.1	5.5	747	14772	0.52
174.5	1.46	287.0	67.4	1.2	5.0	618	15109	0.56
180.5	2.33	275.8	56.4	1.5	7.3	704	13776	0.80
185.5	1.29	345.0	81.2	0.1	5.5	489	10771	0.61
188.5	0.88		74.1	3.2	18.5	1222	27531	6.17

APPENDIX VI (cont...)

CORE B

Depth (cm)	LOI %	Pb	Zn	Cd	Cu	Mn	Fe	Ag
		Heavy metals (mg kg^{-1})						
2	18.34	2471.2	891.9	5.8	42.9	1631	27731	1.31
7.5	6	2105.9	882.0	4.0	20.0	1151	21099	1.31
15.5	3.56	2791.4	1802.1	3.7	14.4	1617	21430	1.10
24.5	3.22	1647.4	1561.4	4.3	12.2	1332	19951	0.74
33.5	3.56	1392.6	1018.2	3.8	10.7	987	19112	0.94
44	2.77	502.4	532.6	1.6	4.1	572	10586	0.60
52.25	3.83	1281.3	878.3	3.5	12.3	967	18981	1.61
59.75	3.03	1106.3	594.2	2.3	10.6	790	16783	1.15
65.75	2.55	937.2	637.1	1.8	8.5	876	18477	0.89
68.25	3.82	1186.3	826.0	2.1	11.2	1193	21808	0.79
69.5	2.94	2630.0	696.0	4.8	17.1	1458	26612	0.18
71.5	3.68	1393.7	629.2	2.5	10.7	982	20580	1.09
75	2.8	854.4	368.0	2.0	8.2	597	17510	1.01
78.25	1.95	1106.3	575.0	2.4	7.4	1034	19578	1.00
80	2.8	1531.7	499.6	3.0	10.9	993	20440	1.15
85.25	3.58	924.8	399.7	2.1	8.4	947	16293	0.64
95	3.48	1887.5	518.1	2.6	11.1	1620	34876	1.51
103	3.08	1629.2	838.1	2.3	9.7	1777	28590	1.17
111.5	4.07	1144.8	425.9	2.4	11.1	1050	19736	1.00
122.5	3.75	1274.3	328.5	2.2	10.4	1125	20901	1.01
133	3.04	1159.3	189.9	2.0	7.9	762	16695	1.25
140	3.88	1553.6	441.0	2.4	11.2	1733	28163	1.09
145	2.02	1105.9	314.2	1.8	7.2	1085	22347	1.17
156.75	3.48	1083.2	318.7	1.7	9.4	986	16873	1.12
164.75	2.45	1920.1	469.1	2.1	10.5	1298	21556	1.22
167	4.79	1538.6	311.5	2.7	13.1	1337	23956	1.58
172.5	4.15	1148.1	203.9	2.2	8.3	898	15826	0.61
178	3.71	2903.4	413.1	4.4	19.6	1941	26582	2.03
184.25	1.68	1250.4	350.1	2.4	9.2	1283	18716	0.35
194.75	1.36	840.9	306.2	1.7	7.6	993	16749	0.91
203.5	2.87	1668.7	371.2	2.1	10.5	1288	18653	0.97
208.5	2.09	1441.3	350.7	2.1	11.4	1297	21493	1.17
212	4.3	1691.4	970.0	3.2	12.9	1582	23399	1.38
214.5	3.67	1783.7	370.2	4.7	12.8	1216	23168	1.44
219	1.49	1251.3	265.1	2.1	9.1	986	21674	0.62
227.5	1.32	965.5	208.1	2.2	7.9	801	18467	0.55
236.75	1.57	875.6	144.8	1.8	6.2	678	12669	0.74
242.25	3.46	1400.9	255.1	2.4	11.2	1118	18088	0.96
246.5	2.21	1221.2	219.0	2.6	8.5	1168	21126	1.29
257.75	3.08	733.5	150.7	1.4	6.7	695	9005	0.43
265.25	2.13	907.7	235.0	1.3	4.6	706	14873	0.61

APPENDIX VI (cont...)

CORE C

Depth (cm)	LOI %	Heavy metals ($mg\ kg^{-1}$) Pb	Zn	Cd	Cu	Mn	Fe	Ag
5	11.29	1897.9	1094.1	4.3	32.8	1315	23430	2.26
15	3.44	1549.9	1115.3	4.2	13.7	899	23251	1.89
24.5	3.01	684.8	733.3	2.6	8.7	689	15510	1.13
31.5	2.98	889.8	908.2	2.6	9.5	854	18971	1.33
38	2.89	884.6	615.8	2.0	8.1	789	16908	0.92
46	2.68	1012.5	536.8	2.0	8.3	934	23959	0.53
53.5	3.39	1300.3	682.6	2.4	8.9	825	20704	1.04
58.5	4.3	1103.6	606.5	2.8	12.5	885	22041	1.09
61	2.89	1021.7	433.3	2.4	7.9	864	22629	0.88
63	2.68	664.6	246.3	1.8	7.8	665	14678	0.46
70.5	2.34	739.4	213.6	2.0	6.9	683	18065	0.38
79.5	2.36	1286.0	359.3	1.9	6.9	1300	23282	0.63

APPENDIX VI (cont...)

CORE D

Depth (cm)	LOI %	Pb	Zn	Cd	Cu	Mn	Fe	Ag
		Heavy metals (mg kg^{-1})						
14.5	2.39	1358.5	1601.0	4.0	10.5	1000	17373	1.77
24	3.62	1345.5	1579.7	3.3	10.6	955	15640	1.60
32.75	4.61	1386.9	1659.2	3.5	11.0	1291	18655	1.43
44.25	3.84	1827.4	2156.3	3.4	11.8	1703	24325	1.95
52.75	4.75	1476.3	1844.4	3.1	11.2	1338	19895	1.92
57	5.8	1663.4	1757.6	3.2	11.8	1630	22140	1.85
61.75	4.94	1636.8	1794.8	3.8	11.4	1592	21329	2.10
68.25	3.65	1664.6	2157.5	3.7	13.6	1599	19364	1.77
77.5	5.73	1933.5	2140.8	4.6	16.8	1590	21726	2.31
86.5	6.95	1702.9	2504.0	4.0	15.0	1363	16588	2.10
90.5	5.01	2183.1	2286.0	6.8	13.4	1564	26046	2.06
93.75	5.3	1809.5	2184.9	6.0	13.0	924	19154	1.92
98	2.54	2896.9	3110.2	8.5	15.4	1239	31021	3.16
102.5	5.65	1987.9	2320.3	7.7	15.7	313	21970	2.25
109.5	4.8	1833.9	2212.9	7.7	14.7	313	25056	2.00
118	3.46	2370.1	3713.4	9.3	16.4	186	26203	2.48
126	3.61	2188.7	3299.3	8.7	13.8	193	21513	2.20
130.75	2.59	2520.4	3666.3	8.8	14.4	326	27159	2.71
136.5	2.76	2035.9	3524.0	8.7	15.0	775	24496	2.15
144.25	2.54	1638.2	3130.9	7.2	11.9	544	18697	1.78
153.25	3.06	2053.4	3263.2	9.2	14.7	1126	23482	2.06
158	4.11	2149.4	2920.9	8.4	14.5	1051	24802	2.23
163	3.92	2286.3	2972.1	8.3	14.7	966	26811	2.89
167.75	2.8	2152.3	3621.5	8.7	16.9	1411	21333	2.67
171.75	2.49	2657.4	3782.7	9.4	17.1	1223	24171	2.60
178.75	2.56	2064.4	3855.7	9.2	14.2	1230	20214	2.18
183	4.19	2770.1	3814.1	11.4	15.3	1752	31013	3.05
185.75	6.21	1909.4	2976.5	7.8	15.0	1222	19419	2.53
189.75	6.47	2604.8	4373.6	12.2	17.9	2326	28109	2.94
193.75	3.72	2238.1	3606.2	9.8	16.3	1356	23151	2.57
197.75	2.64	3345.2	4130.2	11.6	18.1	1516	27808	3.07
211	2.97	3069.6	3797.5	10.7	18.4	1528	28407	3.28

APPENDIX VI (cont...)

CORE E

Depth (cm)	LOI %	Heavy metals ($mg\ kg^{-1}$) Pb	Zn	Cd	Cu	Mn	Fe	Ag
5	8.66	1781.5	1692.0	8.9	21.3	1760	22610	2.88
15	8.96	1648.7	2657.6	8.1	20.3	3016	31265	1.81
25	5.99	1603.4	2280.6	6.2	15.6	2187	27531	1.21
35	6.61	1971.4	2766.3	7.2	17.9	2621	30871	1.69
45	5.2	1626.6	2458.7	6.9	16.4	1919	24506	1.79
53	7.02	1662.6	2631.5	7.9	18.6	2479	26626	1.95
59.25	4.34	2167.5	3113.2	7.6	17.9	2236	28697	2.05
62.5	7.16	2288.0	2890.5	9.7	20.7	2269	28342	1.93
67.75	4.57	2093.3	2927.0	8.2	17.5	2345	28628	2.21
73.25	4.08	2062.3	2764.6	7.7	14.5	2028	28474	2.03
77.5	5.52	2636.2	3606.5	8.9	18.4	2629	34692	1.87
85.25	2.87	2018.3	3786.2	7.5	13.8	1560	29678	1.66
93.75	5.67	2142.4	3391.5	8.7	17.0	1558	25789	2.08

APPENDIX VI (cont...)

CORE F

Depth (cm)	LOI %	Heavy metals (mg kg^{-1}) Pb	Zn	Cd	Cu	Mn	Fe	Ag
4.5	4.87	1443.3	2111.7	6.6	12.9	1617	22595	1.90
13.5	5.38	1439.2	2411.0	6.7	13.2	1964	26249	2.10
21.25	5.42	1942.2	2582.9	7.3	14.6	1893	28111	2.26
27.5	2.26	1430.9	2150.7	5.2	9.7	1661	21953	1.68
35.25	6.95	1869.9	2843.7	7.7	14.8	2203	25815	2.20
45	3.64	1592.5	2631.2	5.9	11.2	2107	24368	1.89
55.5	5.03	1667.7	2494.4	6.9	13.1	1924	25056	1.92
66.5	3.55	1271.3	2025.4	6.0	12.4	1390	19063	1.74
74	8.8	1888.8	2717.8	6.9	13.2	2137	27403	2.06
81	2.92	1247.7	2153.7	5.1	10.0	1296	17968	1.66
87.5	10.31	2594.8	2871.5	7.6	21.1	3058	28784	2.63
94.5	4.77	1739.2	2448.3	6.1	16.0	2249	23205	2.05
105.5	4.63	2088.5	2552.4	5.8	12.9	1552	24776	1.71
116.5	5.54	1414.1	2294.9	5.4	12.5	1728	21031	1.61
125.5	3.95	1544.5	2198.2	5.0	11.1	1537	21191	1.61
132	6.17	1424.6	2141.8	5.6	12.5	1880	13877	1.66
137.5	4.88	1247.8	1646.5	3.6	9.7	1371	19765	1.39
141	7.74	2553.8	2585.0	4.8	15.1	2217	30066	2.50
143.5	6.28	1935.7	2497.0	3.9	12.7	1667	25151	2.22
146	3.13	2179.9	2741.7	4.4	16.4	2330	29657	2.33
148	3.33	2862.1	2216.0	3.7	13.3	1733	31543	3.58
155.25	5.12	1592.3	2240.4	6.8	13.9	1787	21563	2.18
163.25	4.65	1635.2	2149.6	5.9	13.7	1696	21523	2.14
167	5.55	1581.1	1895.0	5.9	14.2	1519	20782	1.96
170.5	5.04	1883.8	2527.6	6.2	13.0	1923	27662	1.63
176.5	3.82	1607.0	1886.4	4.6	9.6	1427	22979	1.86
184.5	6.53	1657.0	2229.5	6.4	13.1	1303	21714	1.76
192	5.05	1389.7	1779.1	3.9	9.6	1388	20862	1.55
197.5	6.81	1904.1	2319.2	7.7	12.8	1766	28058	1.84
203.5	2.4	1578.7	2124.4	4.7	10.7	1154	23393	1.93